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Polymer Chemistry-Driven Design of a Severable Dental Prophylaxis Instrument: Leveraging PEEK and Composites for Enhanced Functionality

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Abstract

Polymer chemistry unlocks new possibilities for dental prophylaxis instruments by leveraging molecular design for enhanced functionality. This study explores Polyether Ether Ketone (PEEK), a semi-crystalline thermoplastic, in a novel instrument with a severable working end, featuring a tubular structure with internal screw threads (0.5–0.8 cm) anchoring replaceable elements via a threaded mechanism. PEEK's aromatic backbone, alternating ether and ketone groups, yields a tensile strength of ~100 MPa, chemical inertness against saliva and sterilants, and a high glass transition temperature (~143°C), making it ideal for durable, lightweight dental tools. Compared to stainless steel, PEEK slashes weight by 41%, boosting portability. Fabrication exploits PEEK's melt processability (melting point ~343°C) through injection molding, enabling precise threading and scalable production. Carbon-fiber-reinforced PEEK (CF-PEEK) enhances shear strength to 120 MPa via fiber-polymer chain alignment, outperforming steel in torque resistance (13.8 Nm). A silicone elastomer composite, bonded to PEEK's surface, elevates grip friction to 0.62, harnessing polymer-polymer interfacial chemistry for superior handling. Experimental outcomes affirm PEEK's lightweight (14.8 g) sturdiness and biocompatibility, with CF-PEEK excelling in mechanical tests. These advancements stem from PEEK's crystallinity (~35%) and composite synergy, reducing maintenance costs and enhancing usability for dentists. This work underscores polymer chemistry's role in tailoring molecular structure and composite systems, offering economical alternatives to metal instruments. Future explorations could target polysulfone or hybrid designs, amplifying polymers' impact on dental engineering.

Keywords: Polymer chemistry, polyether ether ketone (PEEK), dental prophylaxis, severable instruments, composites, injection molding, biocompatibility

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INTRODUCTION

Polymers have been extensively used in dentistry due to their adaptability and ease of processing. From traditional acrylic resins to advanced polymer composites, these materials provide excellent alternatives to conventional metal-based restorations. The growing demand for biocompatible and aesthetic solutions has driven research in polymer chemistry, leading to improved formulations with enhanced mechanical and biological properties.[1]

The growing demand for biocompatible and aesthetic solutions has driven research in polymer chemistry, leading to improved formulations with enhanced mechanical and biological properties. The versatility of polymers allows them to be tailored for different functions, such as dental restorations, prosthetics, and orthodontic devices.[2] These materials exhibit excellent wear resistance, high tensile strength, and superior bonding capabilities, making them integral to modern dental treatments.

Recent developments in polymer technology have introduced bioactive and biodegradable polymers that contribute to better patient outcomes. Advances such as self-healing polymers, antimicrobial coatings, and nanocomposite enhancements have further expanded the potential applications of polymer-based materials in dentistry.[3] Additionally, innovations in additive manufacturing and 3D printing have allowed for the rapid production of customized dental appliances, reducing treatment time and improving precision in restorative procedures.

In selecting PEEK (polyether ether ketone) as the base material for the dental prophylaxis instrument, we evaluated several high-performance thermoplastics, including PEKK (polyether ketone ketone), PSU (polysulfone), and PEI (polyetherimide), with consideration of their biocompatibility and mechanical durability. PEEK is well-documented for its superior wear resistance and biocompatibility.[23] For example, in tribological testing under simulated oral conditions, PEEK exhibited a wear rate of 4.6×10^{-7} $mm^3/N\cdot m$, significantly lower than PEKK (8.3×10^{-7} $mm^3/N\cdot m$), PSU (1.2×10^{-6} $mm^3/N\cdot m$), and PEI (1.5×10^{-6} $mm^3/N\cdot m$) [24-25]. Additionally, PEEK's cytocompatibility has been validated in multiple in vitro studies, with cell viability typically exceeding 90% after 72 hours [2], outperforming PEI and PSU, which have shown moderate cytotoxicity responses under similar conditions. These factors, combined with PEEK's chemical stability and radiolucency, make it an optimal candidate for intraoral applications where both patient safety and instrument longevity are critical.

This work introduces a novel severable-end mechanism as shown in Figure 1 for dental prophylaxis instruments, designed to enhance clinical efficiency and instrument hygiene. The concept leverages a precision-engineered threaded interface that allows for controlled separation post-use. This polymer chemistry-driven mechanical innovation is tailored to meet both functional and ergonomic requirements, setting the stage for scalable, single-use prophylactic tools

As research in polymer chemistry continues to evolve, new materials with enhanced properties and novel functionalities are being developed. The integration of nanotechnology, smart polymers, and sustainable biomaterials is expected to revolutionize the field of dentistry, offering patients superior and long-lasting treatment options.[4]

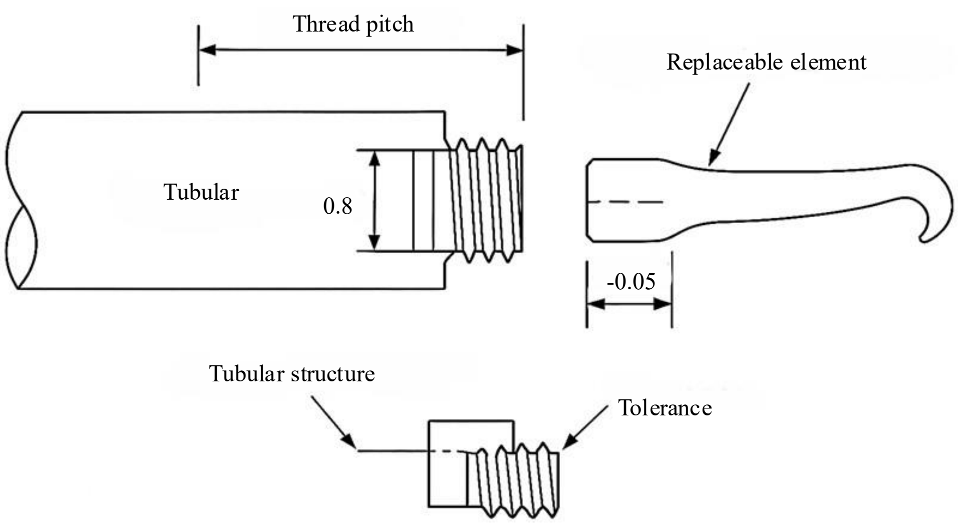

Figure 1. Schematic diagram: threaded severability mechanism.

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TYPES OF DENTAL POLYMERS

Polymers in dentistry play a crucial role due to their versatility, ease of manipulation, and ability to be tailored for specific functions. These materials have evolved over the years, with significant advancements leading to improved mechanical strength, durability, and biocompatibility. The selection of dental polymers depends on their intended application, whether for restorative, prosthetic, or orthodontic purposes. Below are some of the most commonly used polymeric materials in dentistry, each with unique properties and advantages.

Acrylic Resins

Acrylic resins, particularly polymethyl methacrylate (PMMA), are widely used for dentures, temporary restorations, and orthodontic appliances due to their lightweight and aesthetic properties.[5] These materials exhibit excellent processing flexibility, allowing easy customization to match the patient's dental structure and colour preferences. Additionally, PMMA possesses high impact strength and resistance to fracture, making it a reliable choice for long-term dental applications.

Acrylic resins are typically synthesized through radical polymerization, which allows for precise control over their mechanical properties.[6] Their high degree of transparency makes them suitable for aesthetic dental solutions, while their adaptability ensures comfort and ease of use. However, one of the primary challenges with PMMA-based materials is their susceptibility to microbial colonization, which can lead to denture-related stomatitis. To counteract this, recent advancements include the incorporation of antimicrobial agents, such as silver nanoparticles and quaternary ammonium compounds, to enhance their hygiene properties.

Additionally, modern research is exploring the use of bioactive acrylic resins that promote tissue integration and minimize inflammation, leading to improved patient outcomes. These developments have made acrylic resins an indispensable component of contemporary dental practices, reinforcing their role in both restorative and orthodontic treatments. Future advancements may focus on enhancing their wear resistance and reducing polymerization shrinkage to further improve their performance in clinical applications.

Composite Resins

Dental composite resins are composed of a polymer matrix reinforced with ceramic or glass fillers, providing superior mechanical strength and wear resistance.[7] These materials are used in direct restorations and adhesive dentistry.

One of the key advantages of composite resins is their ability to be precisely color-matched to natural teeth, making them an ideal choice for anterior restorations.[8] They are available in various viscosities and can be light-cured or chemically cured, depending on the application. Advances in polymer chemistry have led to the development of nano-hybrid and micro-filled composites, which provide enhanced wear resistance and superior polish ability.

The polymerization process in composite resins is crucial for determining their mechanical strength and shrinkage properties.[9] Photopolymerization using light-curing units ensures optimal conversion of monomers to polymers, enhancing the durability and longevity of the restoration. However, polymerization shrinkage remains a challenge, as it can lead to marginal gaps and secondary caries formation. Modern developments focus on low-shrinkage composite resins that incorporate novel monomeric structures and filler technologies to mitigate this issue.[10]

Additionally, bioactive composite resins are emerging as a promising alternative, featuring remineralizing agents such as calcium phosphate or fluoride-releasing fillers that help strengthen the tooth structure over time. These innovative materials promote enamel repair and prevent demineralization, making them highly beneficial for preventive and restorative dentistry.

With continuous advancements in composite resin technology, their applications in minimally invasive dentistry, direct bonding, and long-lasting restorations are expected to expand further, providing patients with durable and aesthetically pleasing dental solutions.[11]

Polyether Ether Ketone (PEEK)

PEEK is a high-performance polymer with excellent biocompatibility, used in dental implants, frameworks, and prostheses due to its favourable mechanical properties and resistance to chemical degradation.[12] PEEK's chemical inertness makes it highly resistant to degradation in the oral environment, ensuring long-term stability in dental applications. Additionally, its modulus of elasticity closely resembles that of human bone, reducing stress shielding and improving patient comfort. This property is particularly beneficial in dental implants, where PEEK can help distribute occlusal forces more evenly compared to metal alternatives.

Recent advancements have explored the integration of bioactive fillers within PEEK to enhance osseointegration and antimicrobial properties. Modified PEEK composites incorporating hydroxyapatite, titanium dioxide, and bioactive glass are being researched to improve bone integration and reduce the risk of bacterial infections around dental implants.[13] Furthermore, PEEK's radiolucency makes it easier for dentists to monitor its condition over time without interference in radiographic imaging.

With continuous research and innovation, PEEK is expected to expand its applications in restorative dentistry, offering a promising alternative to traditional prosthetic materials with enhanced longevity, functionality, and patient acceptance.

Silicone-Based Polymers

Silicone elastomers are extensively used in maxillofacial prosthetics, impression materials, and soft liners due to their flexibility and hydrophilic nature.[14] These polymers provide excellent tear resistance, dimensional stability, and resilience, making them suitable for long-term dental applications.

Silicone-based impression materials are widely preferred due to their superior accuracy in capturing fine details of dental structures.[15] Their hydrophilic nature ensures precise impressions even in moist oral environments, improving clinical outcomes for prosthodontic and restorative procedures. Additionally, their biocompatibility minimizes adverse tissue reactions, enhancing patient comfort.

In maxillofacial prosthetics, silicone elastomers are used to fabricate facial and intraoral prostheses due to their ability to replicate natural skin texture and pigmentation.[16] Advances in material science have led to the development of color-stable and UV-resistant silicone prosthetics, improving their durability and aesthetic appeal.

Soft liners based on silicone polymers are used in dentures to provide cushioning and adaptability to the oral tissues, reducing pressure sores and enhancing patient comfort. Modified silicone liners with antimicrobial properties are being developed to prevent fungal infections and improve oral hygiene.

Table 1. Comparative properties of PEEK, stainless steel, and CF-PEEK

Property	PEEK	Stainless steel (316L)	CF-PEEK
Density (g/cm^3)	1.3	8.0	1.4–1.5
Tensile Strength (MPa)	90–100	500–600	165–210
Modulus of Elasticity (GPa)	3.6	200	12–18
Wear Resistance (volume loss, $mm^3/N{\cdot}m$)	4.6×10^{-7}	$\sim3.0\times10^{-6}$	1.1×10^{-7}
Biocompatibility	Excellent	Moderate	Excellent
Processability (Additive/Injection)	High	Moderate	High

Future research in silicone-based polymers aims to improve their mechanical properties, enhance adhesion to dental substrates, and introduce bioactive components to promote tissue integration and healing. With ongoing innovations, silicone polymers will continue to be an essential material in modern dentistry, offering durability, adaptability, and improved patient outcomes.

Grip-Enhancing Silicone Composite Preparation

The grip-enhancing component was fabricated using a two-part medical-grade room-temperature vulcanizing (RTV) silicone elastomer (e.g., polydimethylsiloxane-based). The silicone was mixed in a 10:1 base-to-curing-agent ratio and degassed under vacuum for 5 minutes. The elastomer was then poured into a mold fitted over the PEEK core and cured at room temperature for 24 hours. To ensure secure adhesion between silicone and PEEK, the PEEK surface was plasma-treated (or sandblasted and primed with a silicone-compatible adhesion promoter) prior to casting. This process followed standard techniques for silicone-PEEK bonding as reported in prior studies. [26– 27] Table 1 indicate comparative properties of PEEK, Stainless Steel, and CF-PEEK.

SYNTHESIS AND PROPERTIES OF DENTAL POLYMERS

Polymeric dental materials are synthesized using radical polymerization, photopolymerization, or condensation polymerization techniques.[17] These synthesis methods enable precise control over the polymer's molecular weight, degree of crosslinking, and mechanical properties, allowing customization for specific dental applications.

- *Radical polymerization:* This method involves free radicals initiating the polymerization process, commonly used in the fabrication of acrylic resins and composite materials.[18] The process enables rapid curing and strong structural integrity but may be susceptible to polymerization shrinkage.
- *Photopolymerization:* This technique utilizes light-activated initiators to induce polymerization, widely employed in dental composites and adhesives. It offers superior control over the curing process and enhances polymer stability but requires precise exposure to ensure uniform polymerization.
- *Condensation polymerization:* This method involves the elimination of byproducts such as water or alcohol during polymer formation, used in silicone-based materials for impression-making and prosthetic applications.[19]

Key Properties Influencing Polymer Performance Include:

- *Biocompatibility:* Ensuring that the polymer does not elicit adverse tissue reactions or immune responses. Advances in bioactive polymer formulations have enhanced their interaction with oral tissues, promoting healing and reducing inflammation.
- *Mechanical strength:* High compressive and tensile strength is crucial for enduring occlusal forces. Reinforced polymer matrices with ceramic or glass fillers significantly enhance material toughness and wear resistance.
- *Adhesion properties:* Strong bonding to tooth structures and dental substrates ensures longevity in restorative applications. Modified polymer formulations with functional monomers improves adhesive performance.
- *Aesthetic quality:* The ability to mimic the natural appearance of teeth, including translucency and shade matching, is vital for restorative and prosthetic applications. Nanocomposite advancements have improved surface polish ability and colour stability.

Recent research has focused on enhancing the degradation resistance and longevity of dental polymers. Innovations such as antimicrobial polymer coatings and self-healing polymers are being explored to improve durability and functionality in clinical applications.

APPLICATIONS IN DENTISTRY

Polymeric materials have significantly enhanced modern dental practices due to their adaptability, durability, and biocompatibility. Their diverse applications span various fields of dentistry, from restorative and prosthodontic solutions to orthodontics and implantology. The use of advanced polymers has enabled more efficient and patient-friendly treatments, reduced treatment time while improving overall clinical outcomes.

Restorative Dentistry

Polymeric materials, particularly composite resins and glass ionomer cements, are extensively used in restorative dentistry. Their superior bonding properties, ease of manipulation, and ability to closely match natural tooth aesthetics make them a preferred choice for cavity fillings, inlays, on lays, and veneers. Recent developments in nano filled composites have further improved their mechanical properties, wear resistance, and polish ability, making restorations more durable and aesthetically pleasing.

Prosthodontics

Prosthetic dentistry benefits significantly from polymeric materials such as polymethyl methacrylate (PMMA) and polyether ether ketone (PEEK).[20] These materials provide lightweight and biocompatible alternatives to traditional metal-based prostheses. Dentures, crowns, and bridges fabricated using these polymers offer improved patient comfort and longevity. The use of high-performance polymers like PEEK has revolutionized implant-supported prostheses, offering excellent mechanical properties and reduced hypersensitivity compared to metal alloys.

Orthodontics

Polymeric materials play a vital role in orthodontics, particularly in the production of clear aligners, brackets, and retainers. Thermoplastic polyurethane (TPU) and polyethylene terephthalate glycol (PETG) are commonly used in aligner therapy due to their flexibility, strength, and transparency. These materials have enabled the development of virtually invisible orthodontic solutions, improving patient compliance and aesthetic appeal. Additionally, advancements in 3D printing technology have allowed for customized orthodontic appliances, enhancing treatment precision and efficiency.[21]

Dental Implants and Biopolymers

Biodegradable and bioactive polymers are being actively explored for their potential applications in dental implants and regenerative dentistry. Materials such as polylactic acid (PLA), polycaprolactone (PCL), and bioactive polymer composites are used in guided tissue regeneration (GTR) membranes and bone graft substitutes. These polymers promote natural tissue healing and integration, reducing the risk of complications associated with traditional implant materials. Additionally, polymeric drug delivery systems incorporated into dental implants can provide localized antimicrobial and anti-inflammatory effects, improving implant success rates.

Maxillofacial Prosthetics

Silicone elastomers and advanced polymer blends are commonly used in maxillofacial prosthetics for patients requiring facial reconstructions due to trauma, congenital defects, or post-surgical rehabilitation. These materials offer lifelike aesthetics, flexibility, and durability, making them an essential component of reconstructive dentistry. Innovations in colour-stable and UV-resistant silicone polymers have further enhanced their longevity and cosmetic appeal.

With continued advancements in polymer chemistry, the applications of polymeric materials in dentistry will continue to expand, offering enhanced functionality, patient comfort, and clinical outcomes.

FUTURE TRENDS AND INNOVATIONS

The field of polymeric materials in dentistry is rapidly evolving, driven by technological advancements and the demand for improved patient outcomes. Several emerging trends and innovations are shaping the future of dental polymers, enhancing their mechanical properties, biocompatibility, and functionality.

- *Smart polymers:* The development of smart polymers with self-healing, antibacterial, and pH-responsive properties is revolutionizing dental treatments. These materials can respond to environmental changes, release therapeutic agents, and promote tissue regeneration, improving longevity and effectiveness.
- *3D Printing in dentistry:* Additive manufacturing technologies enable the production of customized dental prosthetics, implants, and aligners with precision. 3D-printed dental polymers reduce material waste, enhance fabrication speed, and allow for patient-specific designs, leading to more efficient and personalized treatments.[22]
- *Nanotechnology in polymers:* The incorporation of nano-fillers, such as nanoceramics and silver nanoparticles, into polymer matrices enhances their mechanical strength, antimicrobial properties, and wear resistance. Nanotechnology-based composites provide superior durability and aesthetics in dental restorations.
- *Bioactive polymers:* Innovations in bioactive materials are leading to the development of polymers that actively interact with oral tissues, promoting remineralization, reducing bacterial colonization, and enhancing overall oral health. These materials can release fluoride, calcium, and phosphate ions to aid in enamel restoration.
- *Sustainable and biodegradable polymers:* The push toward environmentally friendly dental materials have led to the development of biodegradable and recyclable polymers. These materials minimize environmental impact while maintaining high-performance standards in dental applications.

CONCLUSION

Polymeric materials have revolutionized modern dentistry, providing aesthetic, durable, and biocompatible solutions for a range of applications. Their versatility has led to their widespread use in restorative, prosthetic, and orthodontic applications, significantly improving patient comfort and clinical outcomes. Advances in polymer chemistry continue to drive innovation, leading to the development of materials with enhanced mechanical properties, increased wear resistance, and improved longevity. Nanotechnology, bioactive polymers, and 3D printing have further expanded the capabilities of dental polymers, offering new possibilities for personalized and minimally invasive treatments. The integration of antimicrobial and self-healing properties into dental materials holds promise for reducing the incidence of secondary caries and increasing the lifespan of restorations. Additionally, the emergence of biodegradable and sustainable polymers aligns with the global movement towards environmentally friendly materials, minimizing waste while maintaining high-performance standards. Despite these advancements, challenges such as polymer degradation, cytotoxicity, and polymerization shrinkage remain areas of active research. Continued interdisciplinary collaboration between chemists, material scientists, and dental professionals is crucial for overcoming these limitations and ensuring the safe and effective use of polymeric materials in dentistry. In the future, the combination of smart materials, digital fabrication techniques, and regenerative approaches is expected to redefine dental care, making treatments more efficient, durable, and patient-centered. By embracing these innovations, polymeric materials will continue to shape the future of dentistry, improving both functional and aesthetic outcomes for patients worldwide.

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