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Recent Advances In Oral And Maxillofacial Prosthetic Materials: A Review

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Abstract
Over the past few decades there has been a remarkable progress and evolution in materials used for maxillofacial prosthetics, transforming the rehabilitation of craniofacial defects. Early materials such as wood, ivory, and vulcanite have been replaced by polymethylmethacrylate and silicone elastomers [1,2]. These materials exhibited improved physical and mechanical properties like flexibility form and integration with surrounding tissues. Modern advancements include high-performance polymers like polyetheretherketone (PEEK) and silicone composites engineered to replicate soft tissue function and appearance [3,4]. Digital workflows incorporating CAD/CAM and 3D printing have significantly accelerated production processes and improved precision [5,6]. Despite these innovations, several challenges persist—particularly concerning colour stability, durability, and the need for long-term clinical validation [7,8]. This review comprehensively explores the evolution of maxillofacial prosthetic materials, with emphasis on emerging silicones, polymers, and composites, along with recent additive manufacturing technologies, biocompatibility, osseointegrated retention systems, clinical outcomes, and future directions.

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I. Introduction

Maxillofacial prosthetics plays a pivotal role in restoring facial form and function, especially when surgical reconstruction is infeasible [1,9]. These prostheses are used to rehabilitate defects of the ear, nose, orbit, and other craniofacial regions due to trauma, malignancy, or congenital deformities [9,10]. The selection of appropriate materials is critical to achieving esthetic, functional, and durable outcomes. Historically, prosthetic materials evolved from rudimentary organic substances to advanced synthetic elastomers and polymers [1]. The 20th century witnessed the introduction of silicones, which offered superior flexibility and tissue-like properties [2,11]. However, the quest for the ideal material continues, driving research into advanced synthetic polymers, novel composites, and digital technologies [4,12].

Evolution of Maxillofacial Prosthetic Materials

The evolution of prosthetic materials reflects the interdisciplinary advancements in polymer science and digital manufacturing. Ancient civilizations used ivory, bone, and metals for prosthetic fabrication [1]. In the 19th century, vulcanized rubber (vulcanite) emerged as a widely used material for dental and facial prosthetics [1]. Later, acrylic resins such as polymethylmethacrylate (PMMA) gained popularity due to ease of manipulation and favourable mechanical properties [1]. The introduction of silicone elastomers in the mid-20th century revolutionized facial prosthetics by offering superior flexibility, biocompatibility, and esthetic outcomes [2,11].

Silicone elastomers are classified into room-temperature-vulcanizing (RTV) and high-temperature-vulcanizing (HTV) types [11,13]. HTV silicones generally exhibit higher tear strength and durability compared to RTV silicones [13]. Hybrid materials—such as silicone copolymers, silphenylene elastomers, and shape-memory polymers—are currently being explored to overcome existing limitations, such as poor mechanical strength and limited longevity [4,14]. Notably, advances in polymer chemistry have led to the development of foam silicones and light-weighted composites to reduce prosthesis weight while maintaining durability [14].

Silicone Elastomers and Polymers

Silicone elastomers remain the cornerstone of maxillofacial prosthetics due to their excellent flexibility, colorability, and biocompatibility [11,15]. However, these materials are prone to UV degradation and mechanical wear over time [15,16]. To enhance performance, researchers are exploring the use of nano-fillers such as titanium dioxide (TiO_2), silica, carbon nanotubes, and cellulose nanofibers, which improve mechanical strength, hardness, and resistance to color fading [3,4,17].

PEEK has emerged as a promising polymer for implant-retained prostheses. It provides excellent mechanical strength, low weight, and favorable esthetics [3]. Studies demonstrate that PEEK frameworks bonded to silicone elastomers offer superior performance compared to conventional PMMA-based systems [3]. Additionally, the incorporation of hybrid polymers and block copolymers has yielded elastomers with enhanced tear resistance and elasticity [14,18] . Furthermore, advancements in foamed silicones and light-weight composites are addressing issues related to prosthesis heaviness and patient comfort [14].

II. Additive Manufacturing And CAD/CAM Technologies

Digital technologies, including CAD/CAM and additive manufacturing, have revolutionized the design and fabrication of maxillofacial prostheses [5,6]. High-resolution imaging modalities such as cone-beam computed tomography (CBCT) and 3D facial scanning are routinely employed to create digital models of craniofacial defects [5,19]. These data enable precise prosthetic designs using CAD software, followed by rapid fabrication through 3D printing [6].

Currently, the most common approach involves printing molds or patterns, followed by silicone processing using traditional methods [6]. However, emerging multi-material 3D printers can create prostheses with varying hardness in different regions, closely replicating natural tissue gradients [5]. Drop-on-demand silicone printing is under experimental investigation for direct prosthesis fabrication [6].

Artificial intelligence (AI)-aided design, augmented reality (AR), and virtual reality (VR) technologies further enhance the customization process [19]. While digital workflows offer significant reductions in fabrication time and cost, key challenges remain regarding the availability of printable biocompatible materials and specialized software for facial prosthetics [7,20].

III. Biocompatibility, Mechanical Properties, And Esthetics

Prosthetic materials must exhibit excellent biocompatibility, appropriate mechanical properties, and superior esthetics [15,16]. Medical-grade silicones are generally inert and safe, though long-term colour stability remains a significant limitation [15,16]. Exposure to ultraviolet light, environmental pollutants, and disinfectants accelerates silicone degradation [16,21]. HTV silicones have demonstrated better colour stability than RTV silicones in long-term studies [13].

Despite improvements, most commercially available silicones fail to match the mechanical properties of natural tissues, with tear strength and elongation at break being primary areas of concern [13,21]. The addition of nano-fillers and hybrid networks has shown promise in overcoming these limitations [17,18].

Esthetic realism is essential for patient satisfaction. Advances in intrinsic and extrinsic colour matching techniques, digital shade guides, and spectrophotometry have improved outcomes, although challenges remain in replicating subtle skin nuances and translucency [21,22]. Typically, facial prostheses require replacement every 1 to 2 years due to degradation [16].

IV. Osseointegrated Implants And Retention Mechanisms

Retention is critical for the success of maxillofacial prostheses. While adhesives, mechanical undercuts, and eyeglass attachments remain in use, osseointegrated craniofacial implants provide superior retention, stability, and patient comfort [10,23]. Titanium implants placed in the mastoid, zygomatic, or frontal bone enable the secure attachment of prostheses using bar/clip mechanisms or magnetic assemblies [10,23].

Magnetic retention systems offer ease of use and esthetic advantages but require precise alignment and robust corrosion-resistant coatings [23]. Adhesives, though non-invasive, often cause skin irritation and provide less durable retention [24].

Clinical studies consistently demonstrate higher satisfaction among patients with implant-retained prostheses compared to adhesive-retained devices, particularly regarding ease of use, esthetics, and psychological well-being [23,25]. Nevertheless, implant failures, especially in irradiated or compromised bone, remain a clinical concern [25].

V. Clinical Outcomes And Patient-Centered Innovations

Maxillofacial prostheses substantially improve patient quality of life, enhancing esthetics, social interactions, and psychological well-being [2]. Surveys report high satisfaction in terms of prosthesis comfort, colour matching, and functional performance, particularly among implant-retained cases [25,26]. Technological innovations such as AR/VR-assisted prosthesis design, patient-specific colour calibration tools, and AI-based design algorithms are being introduced to further personalize treatment outcomes [19,20]. Additionally, portable intraoral scanners and in-clinic 3D printers facilitate same-day prosthesis repairs and reduce the need for multiple visits [19]. Emerging research is also exploring bio-integrated sensors for prosthetic monitoring and the possibility of restoring sensory feedback (osseo-perception) in implant-retained prostheses [27].

VI. Future Directions And Challenges

Future research in maxillofacial prosthetics is focused on developing advanced materials with improved color stability, mechanical resilience, and antimicrobial properties [7,8]. Novel fabrication techniques, including 4D printing and direct silicone printing, aim to enable self-adapting or "smart" prostheses that dynamically respond to environmental stimuli [20,27].

Despite significant progress, there remain unmet needs in terms of long-term color retention, material degradation, and cost-effective solutions for widespread clinical adoption[8,20]. Collaborative efforts between material scientists, prosthodontists, engineers, and digital technologists are essential for translating laboratory advancements into clinical reality[27].

VII. Conclusion

Maxillofacial prosthetic materials have undergone remarkable advancements, transitioning from rudimentary substances to sophisticated polymers, silicones, and composites. The integration of digital technologies has revolutionized prosthesis design, fabrication, and personalization. Despite these strides, challenges related to material longevity, colour stability, and digital workflows persist. Future research will likely focus on bioengineered materials, advanced manufacturing techniques, and personalized prosthetic solutions aimed at optimizing patient outcomes and quality of life.

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