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Review Article

Delving Into Future Directions in Trailblazing Maxillofacial Prosthetic Solutions

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Abstract:
As the field of maxillofacial prosthetics evolves, it faces a dynamic landscape of innovation and improvement. This in-depth analysis emphasizes future developments and groundbreaking solutions in the domain. The review explores the latest advancements in prosthetic technology, focusing on several critical areas. Advances in biomaterials aim to enhance both durability and visual appeal. New biomaterials are crucial in developing prosthetics that are not only functional but also aesthetically pleasing. The significant impact of 3D printing on personalization and accuracy is highlighted. This technology enables precise customization of prosthetics to fit individual patient needs, improving both comfort and effectiveness. The incorporation of artificial intelligence (AI) and machine learning into prosthetic design and fitting procedures is transforming the field. These technologies refine the design process, enhance fitting accuracy, and tailor prosthetics more effectively to each patient. The review investigates trends poised to reshape maxillofacial rehabilitation. It entails a forward-looking view on how innovations such as next-generation 3D printing and bespoke prosthetic solutions are expected to impact patient outcomes and clinical practices. By thoroughly examining contemporary research and emerging technologies, the study illustrates how these advancements have the potential to redefine maxillofacial rehabilitation and enhance patient care. This review offers valuable insights into the future trajectory of facial prosthetic technologies and the significant implications these developments hold for both healthcare providers and patients.

Keywords: Facial Prosthetic Designs, 3D Printing, Advanced Biomaterials, Artificial Intelligence, Maxillofacial Rehabilitation

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Introduction: Maxillofacial prosthetics is a subspecialty of prosthodontics that focuses on replacing and restoring lost or missing structures and functions in the head and neck region using artificial substitutes.[1] These prostheses are essential for replacing missing bone or tissue and restoring crucial oral functions such as swallowing, speech, and chewing.[2] Additionally, prostheses for the face or body may address cosmetic and psychosocial concerns and can be designed to position or shield facial structures during radiation therapy.[3] In some cases, maxillofacial prosthetic treatment is a preferable alternative to reconstructive or plastic surgery, particularly for patients who are in poor health or have extensive defects or trauma.[4] For patients with defects in the maxilla or mandible or face, maxillofacial prosthodontists play a key role in rehabilitation.[5] They are ideally suited to coordinate the multidisciplinary efforts required in this complex rehabilitative process, working with head and neck surgeons, radiation oncologists, oral surgeons, general and specialty dentists, plastic surgeons, neurologists, and speech pathologists. The ultimate goal of maxillofacial prosthetic treatment is to improve the patient's quality of life.[6] Maxillofacial prosthetics is focused on the restoration and/or replacement of stomatognathic and craniofacial structures.[7] These prostheses can be designed for either regular or elective removal, offering flexible solutions tailored to the patient's needs.[8] Following cancer ablation surgery in the head and neck, maxillofacial prosthetics can be crucial in rehabilitating a patient's appearance and functional capabilities, such as mastication, swallowing, and speech.[9] When surgical reconstruction options are limited, a maxillofacial prostheses can restore both function and aesthetics, thereby enhancing the patient's quality of life and psychological well-being.[10] Maxillofacial prosthodontists collaborate closely with oncologic surgeons, physicians, and other members of the cancer care team to achieve optimal treatment outcomes.[11] Maxillofacial deformities, which may result from tumors, congenital anomalies, trauma, or sympathetic ophthalmia, have a significant impact on a person's physical, psychological, social, and familial well-being. These deformities can severely affect mental health, professional performance, and personal life, leading to a reduced quality of life.[12] Historical records indicate that since 3000 BC, alloplastic aids have been used to restore oral functions such as swallowing, speaking, and chewing when bones or tissues are missing.[13] Facial or body prostheses are recommended for psychological and aesthetic reasons, especially when plastic surgery is either too costly or impractical.[14] Ackerman's 1953 definition of maxillofacial prosthetics describes it as a subspecialty of prosthodontics involving the use of artificial substitutes for repairing and reconstructing intraoral and extra oral structures, enhancing appearance, protecting defective tissue, and providing significant psychological benefits.[15] Maxillofacial reconstruction includes artificial replacements for intraoral structures like the temporomandibular joint, maxilla, mandible, palate, tongue, and lips, as well as extra oral structures such as the ear, nose, eye, and other facial features, all tailored to the patient's specific needs (**Figure 1**).[16]

Figure 1: Intra oral & Extra oral Prostheses

Courtsey: Mayank Singh, Akshay Bhushan, Narendra Kumar, and Sharad Chand. Obturator prosthesis for hemimaxillectomy patients. Natl J Maxillofac Surg. 2013 Jan-Jun; 4(1): 117–120.

The history of maxillofacial prosthetics is diverse. Early applications of engineering principles for facial appearance restoration date back to Hippocrates.[17] The Etruscans were notable for their advanced intraoral prostheses, and mummified Egyptians were found with enamel-covered silver eyes, bronze lids, and nasal and auricular prostheses. Romans used artificial eyes for living patients, and ancient Greeks created silver artificial eyes for statues. [18] The 16th century saw Ambroise Paré document the use of artificial eyes, ears, noses, and obturator prostheses, utilizing materials such as papier-mâché, leather, ivory, gold, and silver.[19] By the 19th century, gold, porcelain, and various synthetic materials were used in prosthesis fabrication. The advent of vulcanite and other materials significantly improved prosthetics during World War I.[20] Modern materials include vinyl plastisol, acrylic resins, polyurethanes, latex, and silicone polymers.[21]Silicone polymers are favored for their chemical inertness, strength, and durability, although they have drawbacks such as color degradation and instability.[22]Acrylic resins offer improved versatility and comfort, and various orbital implants restore volume and mobility. Advances in 3D printing technology are transforming maxillofacial reconstruction by providing precise, patient-specific models.[23] The review article highlights these innovations, emphasizing their potential to revolutionize prosthetic design and production, while also exploring future directions in research and industry practices related to 3D-printed maxillofacial prosthetics.[24]

Discussion: Maxillofacial prostheses are broadly divided into restorative and complementary categories. Restorative prostheses aim to replace lost bone or correct facial contour deformities. They can be categorized into internal prostheses, which are situated within the tissue, or external prostheses, such as oral, ocular, or facial prostheses. Complementary prostheses support plastic surgery procedures before, during, or after surgery or during radiotherapy.[25]

Challenges in Prosthesis Stability and Retention: Patients who have undergone a maxillectomy may face several challenges with prosthesis stability and retention. These challenges are influenced by various factors, including the size of the defect, the number of remaining teeth, the amount of healthy tissue available, the quality of the mucosal tissue, exposure to radiotherapy, and the patient's acceptance of the prosthetic treatment. The stability and retention of obturator prostheses (**Figure 2**) are significantly affected by the defect's size and location, the number of remaining teeth, and the support area of the remaining palate.[26]

Figure 2: Obturator Prostheses

Courtsey: Mayank Singh, Akshay Bhushan, Narendra Kumar, and Sharad Chand. Obturator prosthesis for hemimaxillectomy patients. Natl J Maxillofac Surg. 2013 Jan-Jun; 4(1): 117–120.

Larger defects, fewer remaining teeth, and smaller support areas generally result in poorer stability and retention. Total maxillary resections often present a challenging prognosis, necessitating a multidisciplinary approach to create an effective treatment plan, which may involve preserving healthy structures and using bone or skin grafts.[27]
Mandibular Prostheses: Partial or total mandibulectomy disrupts the entire stomatognathic system, making both surgical and prosthetic reconstruction particularly challenging. Larger resections typically result in less favorable outcomes for maintaining dentition. Factors such as tumor size and location, tongue involvement, soft tissue involvement, and the number of remaining teeth after mandibulectomy critically influence the success of restorative treatments.[28] Functional and aesthetic issues frequently arise from surgery, including reduced masticatory efficiency, altered facial appearance, speech difficulties, malocclusion, swallowing problems, decreased quality of life, and xerostomia due to radiotherapy. Mucosupported complete dentures or removable partial prostheses (**Figure 3**) may only partially restore aesthetics, with functional restoration often limited by changes in articulating structures and reduced prosthetic base area.[29]

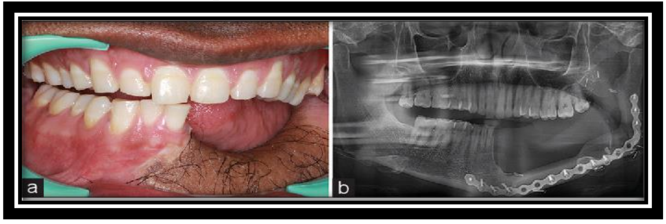

Figure 3: Prostheses in hemimandibulectomy patients

Courtesy: Nag P., Venkat Ratna, Bhagwatkar Tejashree. Prosthetic management of a hemimandibulectomy patient using tilted implant protocol with 3-year follow-up. The Journal of Indian Prosthodontic Society. Jul–Sep 2020; 20(3):326-330.

Tongue Prostheses: Carcinomas commonly affect the lateral posterior surface of the tongue, requiring surgical excision and radiotherapy. Extensive lesions may necessitate resection of the floor of the mouth and part of the tongue, impairing mastication and swallowing, leading to food and liquid accumulation in the oral cavity, and resulting in unclear speech. The removal of the tongue can also destabilize mandibular prostheses in edentulous patients. An artificial tongue (**Figure 4**) with a posterior tilt to guide food toward the oro-pharynx and an anterior lift for articulating phonemes can enhance chewing, swallowing, and speech.[30]Palatography can help reduce sibilant distortions and improve speech clarity. Patients are advised to consult a speech therapist before, during, and after treatment to improve speech and strengthen surrounding muscles for better oral function.[31]

Figure 4: Tongue Prostheses

Courtsey: Muthu Kumar Balasubramaniam, Ahila Singaravel Chidambaranathan, Gokul Shanmugam, and Rajdeep Tah. Rehabilitation of Glossectomy Cases with Tongue Prosthesis: A Literature Review. J Clin Diagn Res. 2016 Feb; 10(2): ZE01–ZE04.

Ocular Prostheses: The partial or total loss of an eye affects not only vision but also a patient's self-esteem and social interactions. Ocular prostheses (**Figure 5**) play a crucial role in helping individuals reintegrate into society, given the essential role eyes play in human connection. These prostheses assist in maintaining the tone of the upper eyelid muscles, preserving the tear duct to prevent eyelash adherence and conjunctival dryness, avoiding eyelid atresia, and protecting the cavity mucosa from debris.[32] Ocular bulb loss can result from various conditions or accidents. Orbital and eyelid surgeries related to ocular prostheses include evisceration, which involves the partial removal of the eye bulb while preserving the sclera; enucleation, which entails the complete removal of the eye bulb while leaving the capsule and oculomotor muscles intact; and exenteration, which involves removing all contents of the orbital cavity and surrounding tissues. A well-fitting ocular prosthesis requires minimal maintenance, generally involving daily cleaning with water and mild soap. The process of creating these prostheses helps patients manage the complex challenges associated with vision loss and ocular mutilation.[33]

Figure 5: Ocular Prostheses

Courtsey: Mayank Singh, Akshay Bhushan, Narendra Kumar, and Sharad Chand. Obturator prosthesis for hemimaxillectomy patients. Natl J Maxillofac Surg. 2013 Jan-Jun; 4(1): 117–120.

Facial Prostheses: Facial prostheses are categorized into nasal, lip, oculo-palpebral, auricular, skull cap, and tracheostomal types, with additional options for large facial reconstructions. These prostheses are designed to reconstruct lost soft and hard tissues, enhancing appearance, boosting self-esteem, and improving quality of life. They also serve various physiological functions: nasal prostheses (**Figure 6**) improve airflow and speech; lip prostheses restore support for chewing, swallowing, and speech, auricular prostheses enhance hearing in noisy environments, skullcap prostheses (**Figure 7**) protect the brain, and tracheostomal prostheses facilitate breathing, speech, and air filtration. Radiotherapy prostheses, also known as radium-holder apparatus, help direct radioactive elements to target tumors while minimizing radiation exposure to surrounding healthy tissues. They are used in brachytherapy or external radiotherapy and are made from resin or silicone. Fabrication involves a collaborative team including a radiotherapist, physicist, and prosthetic dentist, with precise distribution of therapeutic doses planned using computer technology.[34]

Figure 6: Nasal & auricular Prosthesis

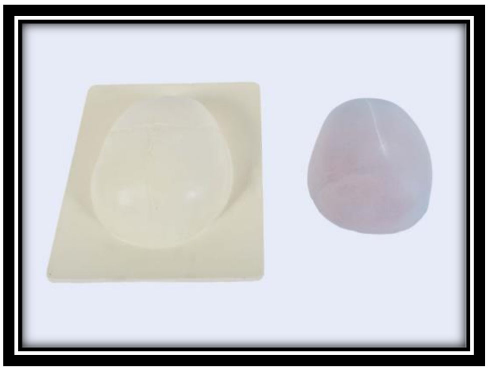

Figure 7: Skull cap

The development of prosthetic techniques has evolved significantly over centuries, transitioning from materials such as curved wood, ivory, and malleable metals to advanced modern materials including silicone block copolymers, polyphosphazenes, Room Temperature Vulcanizing (RTV) silicone, polyvinyl chloride, siphenylenes, and polyurethane.[35] These materials must meet stringent criteria to be suitable for use in prosthetics, including non-toxicity, biocompatibility, dimensional stability, lightweight, low water absorption, color stability, good tear strength, and resistance to skin secretions.[36]Currently, the selection of materials for fabricating maxillofacial prostheses depends on the specific objectives of the rehabilitation procedure. These objectives typically include the restoration of aesthetics, function, and protection of tissue, therapeutic effects, or psychological benefits.[37] Acrylic resin has been utilized successfully for specific types of facial defects, particularly where minimal movement occurs in the tissue bed during function. Its major advantages include its availability, familiar chemical properties, and processing techniques. Acrylic resin allows for both extrinsic and intrinsic coloration.[38]Research by Goiato et al. found that the micro hardness of acrylic resin was not significantly affected by disinfection methods or storage time.[39] However, the main drawback of acrylic resin is its rigidity, which makes it unsuitable for use in highly movable tissue beds, potentially leading to local discomfort and exposure of margins.[40]Acrylic Co-Polymers (Palamed) are soft and elastic, with the fabrication process involving under filling molds to allow for material expansion and foam formation. [41] Although Cantor and Hildestad provided a comprehensive procedure for prosthesis fabrication with acrylic co-polymers, these materials did not gain widespread acceptance due to issues such as poor edge strength, poor durability, degradation upon sunlight exposure, difficult processing and coloration, and a tendency to become tacky, which leads to dust collection and staining.[42] Antonucci and Stansbury have reported the development of new-generation acrylic monomers, oligomers, and macromers that incorporate high-molecular-weight acrylic polymers with molecular blocks of other polymers, such as poly-ether urethane, poly-hydrocarbon, poly-fluoro carbon, and poly-siloxane, to address the shortcomings of traditional acrylic co-polymers.[43] Polyvinyl Chloride & Copolymers were introduced by Chalian VA and Phillips RW for facial restorations.[44] The initial material combined polyvinylchloride, a hard, clear resin, with a plasticizer for processing at low temperatures. Later, a copolymer of 5% to 20% vinyl acetate with vinyl chloride was developed.[45] This thermoplastic material was more flexible and adaptable to both intrinsic and extrinsic coloration but had the drawback of requiring metal molds for curing and exhibiting poor tear strength and color stability.[46] Polyurethane elastomers, described by Juan B et.al. are produced using a catalyst to combine polymers terminating with isocyanate and hydroxyl groups.[47] Polyurethanes offer excellent properties such as flexibility, good edge strength, and color adaptability, with positive cosmetic results.[48] However, the curing process requires precision because isocyanate is moisture-sensitive, and contamination of the mold with water can cause defects and poor curing.[49] Thorough dehydration is necessary before processing if stone molds are used. Silicone elastomers were introduced in 1946 but have only recently been applied to maxillofacial prosthesis fabrication.[50] Silicones are composed of alternating chains of silicone and oxygen, which can be modified by attaching various organic side groups or by cross-linking molecular chains. Silicones demonstrate a range of properties from rigid plastics to elastomers and fluids, and they exhibit good physical properties across a range of temperatures.[51] According to Mohammad SA, silicones resist absorbing organic materials that promote bacterial growth, making them relatively safe and sanitary with simple cleaning.[52]Silicones are vulcanized either by heat (HTV) or room temperature (RTV), each having its own set of advantages and disadvantages. High Temperature Vulcanized (HTV) Silicone is usually a white, opaque, viscous material with a putty-like consistency; available in 1-component or 2-component systems.[53]The catalysts for HTV is dichlorobenzyl peroxide or platinum salts, with fillers added to adjust hardness, strength, and elongation. Polydimethyl siloxane can be added to reduce stiffness or hardness.[54] The vulcanization process requires greater milling of the solid HTV stock elastomer for mixing the catalyst, and cross-linking occurs through free radical addition, with processing temperatures ranging from 180 to 220°C for about 30 minutes under pressure using metal molds.[55] Abdelnabbi et al. found that HTV silicone exhibits exceptional tear strength, tensile strength, elongation percentage, thermal stability, color stability, and chemical stability, making it biologically inert.[56] Room Temperature Vulcanizing (RTV) Silicones are divided into two main categories based on their cross-linking mechanisms.[57] The first category of Room Temperature Vulcanizing (RTV) silicones involves condensation reactions, utilizing reactive groups like silariols (hydroxyl-terminated polysiloxanes), a cross-linking agent such as tetraethyl silicate, and a catalyst like triacetoxy silane. These silicones are often used as extrinsic colorant carriers on the surface of prostheses, with products such as Silastic 382 and 399 serving as examples. The second category involves addition reactions where silyl hydride groups (-SiH) interact with vinyl groups ($CH2=CH-$) in the presence of a platinum catalyst. Although these silicones are designated as RTV, they necessitate heating at 150°C for curing.[58] Recent developments include the use of epoxy resins and stainless steel molds, with examples including Silastic 382, 399, 891, MDX4-4210, Cosmesil, A-2186, and A-2186F. RTV silicones can also be combined with earth pigments to match the patient's skin color.[59] Doootz ER, Koran A, and Craig RG, in 1994, evaluated the impact of accelerated aging on the physical properties of materials such as MDX 4-4210, A-2186, and Cosmesil, concluding that Cosmesil exhibited the most significant effects of aging while MDX 4-4210 showed the least change.[60]In 2003, Aziz T, Waters M, and Jagger R assessed various maxillofacial silicone materials, finding that none possessed ideal properties for prosthetics.[61] Recent innovations in silicone block copolymers aim to address some of the shortcomings of silicone elastomers, such as their low tear strength, elongation, and susceptibility to bacterial or fungal growth, offering significant improvements in these areas.[62] These block copolymers, which include Polydimethylsiloxane (PDMS) and Poly(N,N-dimethylaminoethyl methacrylate) PDMAEMA blocks, exhibit improved tear resistance and bio adhesive properties.[63]Polyphosphazenes, introduced by Gettleman, have potential in maxillofacial prosthetics due to their use as resilient denture liners.[64]Modifications to polyphosphazenes' physical and mechanical properties may be required to meet maxillofacial needs.[65]Research has shown that compounding polyphosphazenes with minimal fillers and adjusting the acrylic-to-rubber ratio can produce a softer material with hardness similar to human skin.[66]Foaming silicones, introduced by Firtell et al., allow for the production of lightweight prostheses.[67] The foaming process involves mixing silicone with a stannous octoate catalyst, releasing gas during vulcanization, which reduces the density of the material. This method requires special equipment to manage gas expansion and venting to avoid defects.[68] Siphenylenes, as described by Lewis and Castleberry, are siloxane copolymers containing methyl and phenyl groups. These pourable, viscous, room-temperature vulcanizing liquids feel more like skin in tactile response. [69] Despite their transparency, even when reinforced with silica fillers, siphenylenes offer desirable properties similar to RTV silicones, including biocompatibility, Ultra Violet and heat resistance, improved edge strength, and color ability.[70]Future directions in maxillofacial prosthetics involve advancements in medical science and engineering, leading to the development of "bionic" organs. These devices, which interface with living tissues to replace or augment natural organs, include bionic eyes, noses, and ears incorporating microchips, transducers, polymers, semiconductors, electronic arrays, and radio transmitters.[71]Research continues in this area, with various models and systems in development. Additionally, advancements in digital technology, particularly rapid prototyping and Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM), have opened new avenues for creating life like prostheses.[72] The use of 3D printing technologies, including techniques like stereolithography (SLA), photopolymer jetting, selective laser sintering (SLS), fused deposition modeling (FDM), and liquid deposition modeling (LDM), allows for the production of complex, precise prostheses. However, challenges remain in commercializing 3D-printed maxillofacial prostheses, such as developing new biocompatible materials that provide the necessary strength, shape retention, and color stability. The integration of CAD/CAM with digital skin color matching systems like the E-Skin spectromatch spectrometer, which uses a digital library of skin tones to match patient skin color, represents a significant advancement. Despite the higher costs, computer numerical control (CNC) machining offers invaluable accuracy and precision.[73]

Role of Dental Labs in Maxillofacial Prosthetics: Dental labs are essential in designing and crafting customized prosthetics to meet individual needs. This includes producing facial prostheses such as ears, noses, and eyes, as well as intraoral prostheses like obturators and speech aids. The meticulous nature of these prosthetics requires significant skill and artistry. The success of prosthetic solutions relies on the smooth collaboration between dental lab technicians and the clinical team, which comprises prosthodontists, surgeons, and other healthcare professionals.[74] Precise molds, models, and prosthetics from dental labs ensure that the final product is both visually appealing and functional. Technological advancements such as innovations in digital technology, including sophisticated imaging, 3D printing, CAD, and CAM, have profoundly transformed the design and manufacturing of prosthetics. These innovations set new benchmarks for accuracy and customization. [75]Dental labs are at the forefront of integrating these technologies, which enhances the precision, efficiency, and cost-effectiveness of prosthetic treatments.[76] Ongoing research in these labs aims to identify superior materials and techniques, ensuring that prosthetics are increasingly durable, comfortable, and lifelike.[77]Beyond the fabrication phase, dental labs also offer crucial support for prosthetic care and maintenance, essential for their longevity and comfort. This assistance is vital for helping patients adapt to and integrate their new prosthetics into daily life.[78] As digital technologies continue to advance, their adoption in dental practices and laboratories is becoming increasingly common. While CAD/CAM technology has traditionally been applied to intraoral components, restorations, and 3D-printed surgical and endodontic guides, its potential for maxillofacial applications is becoming more evident. An innovative example of CAD/CAM technology in maxillofacial prosthetics is a case where a 3D-printed surgical guide is used.[79] This approach allowed for precise and predictable implant placement for a maxillofacial prosthesis. Implants (Nobel Replace Select, Nobel Biocare) are virtually planned, with one positioned at the upper left zygoma and two at the temporal bone in the supraorbital area. [80]Anchor pins are placed at the nasion and the posterior aspect of the zygoma (**Figure 8**).

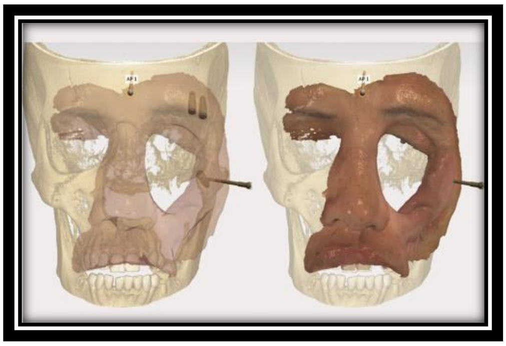

Figure 8: CAD/ CAM in maxillofacial prosthetics

Implants and anchor pins positioned before surgical guide is designed

Courtsey: Vinicus Machado, Filipe Bettoni Cruz de Castro, Carlos Jaeger , Elizabeth Rodrigues Alfenas , Nelson R F A Silva. CAD/CAM Beyond Intraoral Restorations: Maxillofacial Implant Guide. 2019 Jul/Aug; 40(7):466-472.

A surgical guide was designed to ensure accurate implant placement, with its STL file produced and 3D-printed using an SLA Form 2 printer (Formlabs).[81] The guide is utilized for implant surgery with the patient under full sedation, using a flapless approach. After a six-month healing period, a customized maxillofacial prosthetic mask is created. This involved facial recording, selecting a retention method, crafting the ocular component, sculpting the prosthesis, testing the fit, and applying intrinsic and extrinsic painting. The final outcome highlights the effectiveness of integrating advanced digital technologies with traditional prosthetic techniques to enhance patient results.[82]

Future Directions: As we explore the future directions in maxillofacial prosthetic solutions, it is evident that the field is on the cusp of transformative change. The integration of advanced biomaterials is enhancing both durability and aesthetic appeal, paving the way for more lifelike and functional prosthetics. The advent of 3D printing technology has revolutionized personalization and accuracy, allowing for solutions that are tailored to individual patient needs with unprecedented precision. These innovations are advancing the capabilities of maxillofacial prosthetics and setting new standards for patient care. As these technologies continue to evolve, they promise to further reshape the landscape of maxillofacial prosthetics. Future advancements will likely drive significant improvements in both clinical practice and patient satisfaction, offering new possibilities for customized and effective rehabilitation solutions.[83]

Conclusion: The future of maxillofacial prosthetics holds immense potential. Ongoing research and development are expected to lead to continued advancements that will redefine the boundaries of what is possible, ultimately enhancing patient outcomes and care. The precise orientation of the iris is crucial for the success of an ocular prosthesis. Achieving optimal esthetic outcomes can be facilitated through objective iris-positioning techniques that rely on a basic toolkit and minimal patient cooperation. Customizing an ocular prosthesis is a challenging process that requires accuracy and precision, with emerging advanced techniques assisting clinicians in creating prostheses that ensure secure, comfortable fits while maintaining a natural appearance. Maxillofacial prostheses, which restore various orofacial defects, have evolved from ancient treatment modalities to sophisticated solutions that significantly improve patient quality of life. The current advancements are promising, and there are positive expectations for the future, marking an exciting era in the field of maxillofacial prosthetics.

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