



The Role and Future of Synthetic Gbr Membranes in Modern Oral and Maxillofacial Surgery

 Betül Gedik,  Mehmet Ali Erdem

Istanbul University, Dentistry Faculty, Oral and Maxillofacial Surgery Department, Istanbul, Türkiye

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Abstract

Guided Bone Regeneration (GBR) membranes play a crucial role in modern oral and maxillofacial surgery by providing a barrier to facilitate bone regeneration in challenging clinical scenarios. Synthetic GBR membranes, as alternatives to natural material-based membranes, offer significant advantages due to their biocompatibility, controlled biodegradation, mechanical stability, and ease of customization. These membranes are engineered to minimize inflammatory reactions, synchronize degradation with the bone healing process, and prevent soft tissue invasion into bone defects.

Materials such as polylactic acid (PLA), polycaprolactone (PCL), and polyglycolic acid (PGA) are commonly employed in their fabrication, with composite designs incorporating bioactive ceramics to enhance osteoconductive and osteoinductive properties. Advanced manufacturing techniques, including electrospinning and 3D printing, allow for patient-specific designs, multilayered architectures, and integration of bioactive molecules.

Clinical applications in oral and maxillofacial surgery include alveolar ridge preservation, peri-implant bone defect management, repair of defects following cyst or tumor resection, and sinus augmentation procedures. Synthetic membranes have demonstrated effectiveness in maintaining bone volume, stabilizing graft materials, and promoting osteogenesis, thereby optimizing outcomes for dental implant therapy and other reconstructive procedures.

This review explores the properties, material selection, and clinical applications of synthetic GBR membranes, emphasizing their role in advancing bone regeneration techniques. Additionally, future directions and innovations in membrane design, including biofunctionalization and multi-material approaches, are discussed to highlight the potential for improving clinical success in regenerative therapies.

Keywords: Bone regeneration, membranes, oral surgery, biocompatible materials.

INTRODUCTION

Bone regeneration is one of the main goals of dentistry and oral and maxillofacial surgery, and is of critical importance in the treatment of bone loss, especially as a result of trauma, tumor resections, congenital anomalies, and periodontal diseases. Guided bone regeneration (GBR) techniques developed in line with this goal have become an integral part of modern surgical practices in the repair of bone defects. GBR supports new bone formation by taking advantage of the different healing rates of bone and soft tissue through the use of a biocompatible barrier membrane (1).

Barrier membranes are one of the most important components that guide the regenerative process in GBR procedures. These membranes prevent fibroblasts and other rapidly proliferating soft tissue cells from entering the bone regeneration area during the healing process, while supporting the proliferation and functions of osteoblasts and other bone cells (2). The membranes used have features such as biocompatibility, mechanical durability, appropriate degradation profile, and reduced risk of infection. Synthetic GBR membranes stand out with their advantages such as lower cost, no risk of infection, and long shelf life compared to natural membranes. These polymer-based

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Corresponding Author: Betül Gedik,

E-mail: betulgedik@istanbul.edu.tr

Control of the pore structure also has an important effect on mechanical strength. Large and irregular pores reduce the strength of the membrane, while optimized pore structures facilitate cell migration and increase mechanical stability. In addition, multilayer membrane designs optimize both durability and biological activity by providing different mechanical properties in different layers (11).

4. Easy Production and Customizability: They can be produced with desired properties thanks to their polymer structures. Synthetic GBR (Guided Bone Regeneration) membranes have a wide range of use in clinical and research areas due to their easy production methods and customizable structures. The production of these membranes from synthetic polymers allows the material properties and membrane design to be adapted according to the desired biological and mechanical requirements (12). Synthetic GBR membranes can be easily produced with advanced production techniques such as electrospinning, solvent casting, compression molding and 3D printing. In particular, the electrospinning method provides an ideal environment for cell proliferation and vascularization by providing high porosity and controlled fiber dimensions (13). 3D printing technology enables the production of multilayer membranes with complex geometries and enables membrane designs for patient-specific applications (14).

Synthetic membranes allow properties such as biodegradability, mechanical strength, and surface biocompatibility to be controlled. For example, by using polymers such as polylactic acid (PLA) and poly(lactic-co-glycolic acid) (PLGA), the degradation time of the membrane can be optimized by changing the monomer ratios. This allows biodegradation times compatible with the time frame required for bone regeneration to be achieved. With the help of advanced production methods and biocompatible materials, GBR membranes can be customized according to patient-specific needs. For example, 3D printing technology can produce specially shaped membranes suitable for tooth loss or bone defects. In addition, biological functions can be increased by adding antimicrobial agents, growth factors, or osteoinductive molecules. Synthetic membranes enable the design of different layers according to mechanical and biological properties. For example, the outer layer can be optimized to prevent soft tissue invasion, while the inner layer can be optimized to promote bone cell proliferation and vascularization. Such multilayered structures play an important role in accelerating bone regeneration.

MATERIAL SELECTION IN SYNTHETIC GBR MEMBRANES

The raw materials of synthetic GBR membranes are selected and combined according to biological and mechanical requirements. PLA (polylactic acid), PCL (polycaprolactone), PGA (polyglycolic acid), PU (polyurethane) and composite materials each offer solutions for different clinical needs. The development and use of these materials enable more effective and patient-centered treatment approaches in the field of bone regeneration.

Polylactic acid (PLA) is frequently preferred in the production of synthetic GBR membranes due to its high biocompatibility and controlled degradation properties. PLA's biodegradability, hydrophilic structure and crystallization capacity provide a suitable environment for bone regeneration. During degradation, it turns into lactic acid and forms a biologically tolerated byproduct. In addition, its mechanical strength is sufficient to support bone healing (15).

Polycaprolactone (PCL) is an ideal material in cases where long-term support is required, as it has a low degradation rate. It provides convenience in surgical applications thanks to its elasticity and flexibility. In addition, when combined with bio-ceramic particles, osteoinductive properties can be provided (16). The controlled degradation rate of PCL provides advantages in terms of cellular proliferation and tissue integration.

Polyglycolic acid (PGA) is known for its rapid biodegradation properties and is generally suitable for situations requiring short-term support. Due to its hydrophilic structure, it easily absorbs water during degradation, facilitating cell migration and proliferation (17). PGA-based membranes can rapidly react with biologically active molecules and accelerate regeneration processes. However, due to its low mechanical strength alone, it is usually used in combination with other polymers (18).

Polyurethane (PU) stands out as a polymer that provides long-term durability and elasticity. PU membranes have a wide range of uses with their controlled degradation times and high elasticity properties. In addition, biocompatibility can be increased and antimicrobial properties can be provided with surface modifications of PU (19). These properties make PU a suitable material for use in complex bone defects.

Composite membranes are produced by combining different polymers and bioceramics and provide both mechanical and biological advantages. For example, hydroxyapatite-reinforced PLA-PCL membranes optimize mechanical strength while increasing osteoconductive properties (20). In addition, the addition of bioceramics regulates the pore structure of the membrane, promoting cellular infiltration and vascularization. Another advantage of composite membranes is that their degradation profiles can be controlled using different components. For example, combining fast-degrading PGA with slow-degrading PCL can provide optimal support at different stages of the regeneration process (21).

APPLICATIONS IN ORAL AND MAXILLOFACIAL SURGERY

Synthetic GBR membranes play a critical role in bone regeneration and defect management in oral and maxillofacial surgery. Used in various indications, these membranes form an effective barrier to maintain bone stability, prevent soft tissue invasion, and promote osteogenic activity. In clinical applications, the selection of these materials should be made according to the patient's specific needs and should be used with the right techniques to provide optimal treatment results. The main areas of use of synthetic GBR membranes in jaw surgery are reviewed in detail below.

1. Prevention of Alveolar Bone Resorption:

Losses in alveolar bone volume after tooth extraction are one of the common problems in oral surgery. Bone loss can make implant placement difficult and compromise long-term implant stability. Synthetic GBR membranes act as an effective barrier to prevent this situation. It is known that while preventing soft tissue invasion into the bone defect, osteoblasts promote bone formation. Membranes produced from biodegradable polymers, especially polylactic acid (PLA) and polycaprolactone (PCL), offer the advantage of being able to self-resorb without the need for surgical intervention (20). Clinical studies have shown that these membranes maintain bone volume and increase the success of implant treatment (22).

2. Treatment of Peri-Implant Bone Defects:

Synthetic GBR membranes are used together with graft materials to support bone regeneration in bone losses caused by peri-implantitis or trauma (Figure 2). These membranes optimize osteoconductive and osteoinductive processes by stabilizing the bone defect (23). The long-term durability of PCL-based membranes provides stability in the peri-implant region while adapting to biological processes provides an advantage (24). It has been reported that these membranes provide improved clinical results, especially in bone losses caused by peri-implantitis (23).

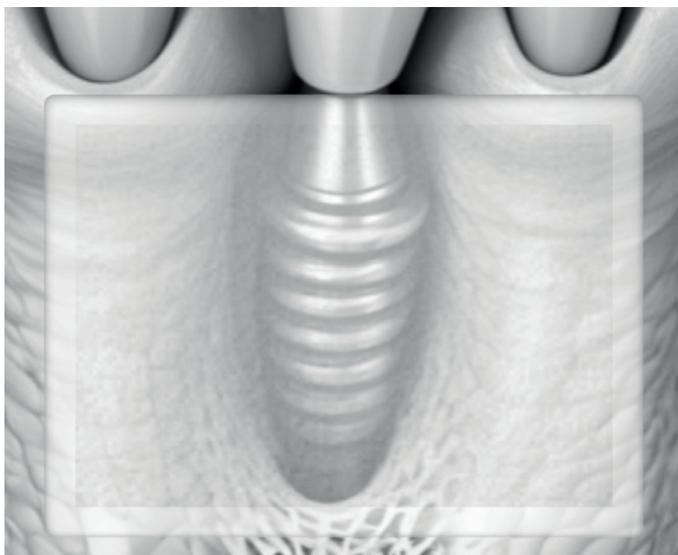


Figure 2. Application of synthetic membrane for treatment of peri-implant bone defects

3. Repair of Defects After Cyst and Tumor Resection:

In maxillofacial surgery, cyst or tumor resections can cause large bone defects. In the treatment of such defects, GBR membranes create a suitable microenvironment for bone regeneration when applied together with graft materials. The mechanical durability and biological compatibility of composite membranes are the reasons why they are preferred especially in large defects (25). The application of membranes to the defect area encourages osteoblasts to become active and accelerates the bone formation process (25).

4. Sinus Lift Procedures:

Maxillary sinus augmentation is a procedure frequently used in cases where the amount of bone is insufficient. During the sinus lift procedure, synthetic membranes are used to stabilize the graft material and prevent soft tissue invasion into the sinus cavity. Since these membranes support bone formation by increasing osteogenic activity in the sinus floor, it has been reported that PLA-based membranes in particular provide successful results in sinus augmentation procedures (26).

5. Repair of Traumatic and Congenital Defects:

Maxillofacial traumas and congenital anomalies can lead to serious losses in bone tissue. Synthetic GBR membranes offer an ideal solution for bone regeneration in the treatment of such defects. Membranes accelerate the bone healing process and improve treatment results when applied together with graft materials. In traumatic cases, the mechanical durability and biological compatibility of the membranes reduce the risk of complications and ensure successful clinical results. In recent years, in addition to traumatic and congenital defects, the use of GBR membranes has also been used in endodontic surgery indications. Various studies on the use of GBR membranes for better regeneration and flawless healing in defects in the apical region are included in the literature (27).

ADVANTAGES AND DISADVANTAGES OF SYNTHETIC GBR MEMBRANES

Synthetic membranes are becoming increasingly widespread in clinical applications due to their cost-effectiveness and ease of production. However, these membranes have some limitations as well as their advantages. The advantages and disadvantages of synthetic GBR membranes are examined in detail below.

1. More Economical Compared to Natural Membranes

The production processes of synthetic GBR membranes are less costly compared to naturally sourced membranes. Biodegradable polymers such as polylactic acid (PLA), polycaprolactone (PCL), and polyglycolic acid (PGA) are easily manufactured on an industrial scale. This makes synthetic membranes more economically accessible. Especially in the treatment of large bone defects, the cost factor is an important advantage for the patient and the clinician (28).

2. No Risk of Infectious Diseases

Natural membranes generally carry the risk of infection and pathogen transmission since they are obtained from animal sources. In contrast, synthetic membranes are produced entirely in laboratory environments and do not contain animal products. Therefore, there is no risk of infectious diseases. In addition, this feature makes synthetic membranes a more attractive option for patient groups with ethical concerns.

In recent years, studies have focused on reducing the risk of infection, one of the most common complications encountered in surgeries with membrane indications (29). For this purpose, studies on synthetic membranes containing antibacterial agents, which are considered susceptible to infection in laboratory settings, have been focused on (29).

3. Ease of Storage and Transportation

Synthetic membranes stand out with their long shelf life and stability properties. They are resistant to various temperature conditions and can be stored for long periods without deterioration. This feature provides a significant logistical advantage, especially for large surgical centers and clinics in developing countries. In addition, unlike natural membranes, synthetic membranes require fewer special storage conditions.

4. Lack of Biological Activity

Natural membranes biologically support bone regeneration with the help of their osteoinductive and osteoconductive properties. However, synthetic membranes generally do not have this biological activity. For example, while natural collagen-based membranes promote cell migration and tissue integration, synthetic membranes play a passive role in this process (30). Since this biological deficiency slows down the bone healing process in some cases, the results of osteogenic factor additions to the membranes in studies on synthetic membranes are still being discussed by researchers (31).

5. Side Effects of Degradation Products

Products formed during the biological degradation of some synthetic polymers can cause inflammation in the surrounding tissues. For example, degradation products of materials such as polylactic acid (PLA) and polyglycolic acid (PGA) can create a local acidic environment and negatively affect the cellular response, which can sometimes last for months (32, 33). This situation can increase the risk of complications, especially in sensitive patient groups, and limit the clinical effectiveness of the membrane.

When evaluating the inflammatory potential of synthetic GBR membranes, it is important to consider factors such as the degradation rates of the polymers, the nature of the degradation products, and the tissue response at the application site. In clinical applications, appropriate membrane selection and patient monitoring are critical to minimize the risk of inflammation.

THE FUTURE OF SYNTHETIC GBR MEMBRANES

In order to increase the clinical success rates of synthetic GBR membranes and address a wider range of applications, advances in biomaterial science and technology are shaping future innovations in this field. In particular, innovative approaches such as nanotechnology, bioactive coatings, and 3D printing techniques offer promising solutions to optimize the performance of synthetic GBR membranes.

Nanotechnology is a powerful tool to improve the mechanical and biological properties of synthetic GBR membranes. Nanofibrous structures increase cellular adhesion, proliferation, and osteogenic differentiation (34). Such membranes allow cells to behave as they would in a natural extracellular matrix environment. Nanofibrous membranes, especially those produced by electrospinning, provide a combination of biomechanical and biological properties necessary for bone regeneration (35). Studies have shown that nanofibrous membranes support the

adhesion and differentiation of osteoblast cells and accelerate bone regeneration (36). In addition, nanotechnological modifications optimize the degradation rate of membranes, thus providing a more controlled biological response.

The use of bioactive coatings to enhance the biological activity of synthetic membranes is one of the most researched topics today. Membranes coated with growth factors (e.g., BMP-2 and VEGF), antibiotics, and other biomolecules can accelerate bone regeneration and reduce the risk of infection (37). Membranes enriched with growth factors enhance osteogenic activity while also optimizing tissue healing by promoting neovascularization. For example, a study published in 2015 reported that membranes containing heparin-stabilized growth factors significantly increased bone regeneration (38). In addition, antibiotic-coated membranes may offer an effective strategy to prevent surgical site infections.

3D printing technologies are revolutionizing the production of synthetic GBR membranes to meet patient-specific treatment needs (Figure 3). Membranes produced by 3D printing can both improve anatomical fit and meet the mechanical and biological requirements specific to individual patients' bone defects. This technology optimizes the micro- and macrostructures of polymer matrices, increasing both the mechanical strength and biocompatibility of membranes (39). In addition, 3D-printed membranes can make treatment processes more effective by providing controlled drug release. For example, there is evidence that drug-loaded 3D-printed GBR membranes provide both antibacterial properties and osteogenic support (40).

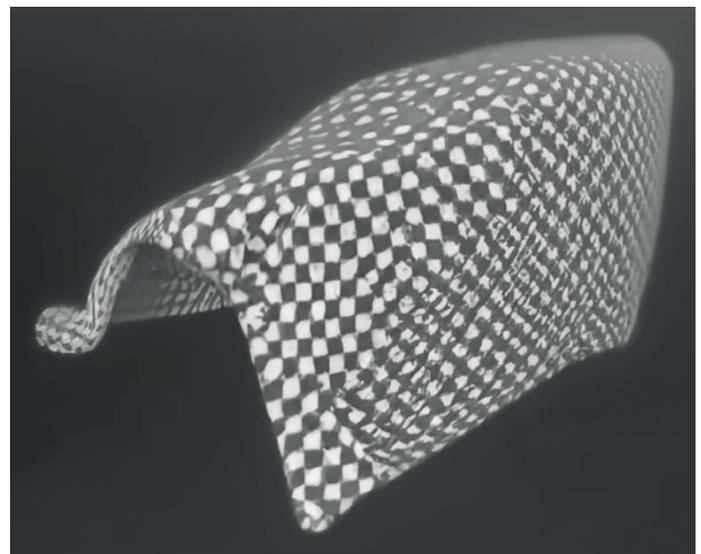


Figure 3. 3D-printed membrane to meet patient-specific needs
Development studies are ongoing to further improve the performance of existing materials in synthetic GBR membranes and to provide more effective solutions to clinical needs. In this context, innovations in smart materials, hybrid and composite structures, and controlled degradation properties are other promising areas to increase the effectiveness of synthetic GBR membranes.

Materials that are sensitive to environmental stimuli (such as pH, temperature, or biochemical factors) are an innovative approach that can improve the application of GBR membranes in jaw surgery. For example, membranes that are sensitive to changing pH levels during inflammatory processes can provide controlled drug release at the target site. In addition, polymers that are sensitive to temperature or enzymatic activity can optimize the treatment process by becoming active only in the areas where it is needed.

Combining different polymers and bioceramics is an effective strategy to increase the mechanical strength and biological activity of synthetic GBR membranes. For example, hybrid membranes consisting of a combination of polycaprolactone (PCL) and hydroxyapatite (HA) can offer both bone-like mechanical properties and osteoinductive capacity. In addition, bioceramic-added composite structures can increase the biocompatibility of the membrane, while promoting the adhesion and proliferation of bone cells. This approach has the potential to provide a more durable and biologically active barrier in the treatment of large bone defects.

The compatibility of the degradation rate of synthetic membranes with the regeneration process is critical for successful treatment. New formulations and material modifications can control the degradation times of membranes, allowing them to dissolve in parallel with the treatment process. For example, slow-degrading polymers such as polylactic acid (PLA) can provide advantages in long-term regeneration processes, while faster-degrading polymers such as polyglycolic acid (PGA) are suitable for situations where a short-term barrier is needed. In addition, controlled degradation properties can reduce the risk of inflammation and minimize unwanted side effects during bone regeneration.

CONCLUSION

Synthetic GBR (Guided Bone Regeneration) membranes offer an effective, reliable and versatile solution for bone regeneration and defect repair in oral and maxillofacial surgery. As a result of their superior properties such as biocompatibility, controlled biodegradation, mechanical durability and customizability, they not only provide alternatives to existing natural materials but also bring innovative approaches to clinical applications. Controlled modification of polymer-based structures allows the design of membranes that are suitable for patient and treatment-specific needs.

Clinical studies and advances in advanced material science increase the effectiveness and applicability of synthetic GBR membranes. In particular, innovative studies on increasing biocompatibility, optimizing mechanical durability and expanding biological functions strengthen the future potential of these materials. In addition, production techniques such as 3D printing and electrospinning provide significant contributions to individualized treatment by offering patient-specific solutions.

In conclusion, the development of synthetic GBR membranes and the widespread use of their applications significant-

ly transform regenerative treatment approaches in oral and maxillofacial surgery. In the future, it is anticipated that these membranes will be enriched with antimicrobial agents, growth factors and other biological agents to further improve treatment outcomes. Synthetic GBR membranes will continue to be one of the cornerstones of innovative and patient-centered treatment methods in modern oral and maxillofacial surgery.

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