Vertical Bone Augmentation Using a Pre-Formed Magnesium Barrier Membrane on a 3D-printed Model – A Case Report

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The restoration of edentulous jaws with dental implants has become a cornerstone of oral rehabilitation. However, extensive bone defects and especially vertical ridge deficiencies present a significant challenge to clinicians. This case report presents the utilization of a resorbable magnesium barrier membrane and magnesium screws for vertical bone augmentation, showcasing magnesium's unique properties-biocompatibility, mechanical strength, and resorbability as a promising alternative to both resorbable and non-resorbable membranes. A 49-year-old male with extensive bone deficiency in the maxillary premolar region underwent vertical ridge augmentation using a xenogenic bone substitute material, a pre-shaped magnesium membrane, and magnesium screws. Preoperative 3D printing and manual defect reconstruction provided precise planning and reduced intraoperative time. Magnesium membranes combine the mechanical properties of non-resorbable materials while also reducing patient morbidity by eliminating the need for second-stage surgery for their removal. 3D printing and pre-surgical planning optimize efficiency and execution of the procedure. To the best of our knowledge, this is the first report of guided bone regeneration using a pre-shaped magnesium membrane designed on a 3D-printed model. While early results are encouraging, further research is needed to validate the long-term efficacy of magnesium-based materials. The results of our case report highlight the potential of personalized, material-driven solutions for the treatment of complex cases in dental implantology.
Keywords: guided bone regeneration, magnesium, bone screws, biocompatible materials, alveolar ridge augmentation, xenograft.

1. INTRODUCTION

The restoration of partially or fully edentulous jaws with dental implants has become the gold standard in the field of dentistry. Large bone defects present a clinical challenge for oral surgeons and dental implantologists performing bone regeneration procedures.

Bone deficiencies could result from trauma, inflammation, benign or malignant tumors and other causes [1]. Several authors proposed classifications for alveolar bone defects over the years – from Seibert (1983) [2], Misch and Judy (1987) [3] to more recently Terheyden (2010) [4]. The common theme between them is characterization of bone loss as horizontal, vertical or a combination of the two. Small horizontal defects are typically restored with guided bone regeneration, whereas vertical bone loss can be substantially more difficult to perform. Various techniques have been proposed, each with its own indications, as well as challenges and limitations [5].

Autogenous block grafting, considered by some as the "gold standard" in bone regeneration due to its osteogenic, osteoinductive and osteoconductive qualities [5]. It has, however, one major drawback – the necessity for an additional operation to create a donor site (intra- or extraoral), increasing patient morbidity and discomfort [6]. Moreover, autogenous bone resorbs quicker and at a larger extent compared to allogenic, xenogenic or synthetic materials [6].

Guided bone regeneration (GBR) involves covering the defect with a barrier membrane, preventing epithelium and connective tissue ingrowth, as well as space maintenance, allowing for bone apposition during the healing period [6, 7]. Non-resorbable membranes such as titanium mesh, expanded or dense polytetrafluorethylene (PTFE) membranes are the preferred choice as they prevent soft tissue collapse over the graft [5]. They are also stabilized with titanium pins. Furthermore, the addition of bone substitute materials aids in space maintenance, and, depending on the material, osteogenesis, osteoinduction and/or osteoconduction could be achieved [5, 8]. The success rate of GBR procedures depends on the size of the defect, formation of new blood vessels inside the graft, permitted by the material porosity, as well as blood clot stabilization [4, 5].

Distraction osteogenesis is a complex technique implemented from orthopedic surgery. It involves segmentation of the alveolar bone, placement of a special device that uses controlled forces to coronally displace the divided segment, allowing for bone to form in the created gap [5]. Due to the scarcity of data, among other factors, its application in dentistry is rather limited [9].

Regardless of the technique, soft tissue management is critical upon increasing vertical ridge dimensions. Tension-free primary closure of the wound is usually achieved through flap mobilization [4, 5]. This comes at the expense

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of attached gingiva, which if left uncorrected prior to or after implant placement, could lead to subsequent bone soft tissue loss [10].

Magnesium and its alloys have been increasingly studied and implemented in regeneration procedures, due to their promising qualities. These include good mechanical properties resembling human bone tissue, biocompatibility and low toxicity, as well as resorbability when in contact with a biological system [11, 12]. Magnesium ions reportedly induce bone formation by activating osteoblasts [13]. Additionally, they inhibit osteoclasts, limiting bone resorption [13]. Magnesium-containing materials express osteogenic properties through several biologic pathways. Magnesium ions (Mg^{2+}) released during membrane degradation stimulate the proliferation and differentiation of osteoblasts, while also modulating the local inflammatory environment, facilitating bone healing [14]. They also activate signaling cascades that are critical for bone regeneration, such as the Wnt/β-catenin and BMP pathways [14]. Magnesium also supports the formation of new blood vessels, which is crucial for supplying nutrients and oxygen to the regenerating bone tissue [14]. Magnesium alloys have been used as medical implants for orthopedic and cardiac surgery [11]. More recently, they have been applied in bone regeneration procedures for the purposes of dental implantology.

Digital technologies have been increasingly utilized in several medical fields. Anatomic and surgical models are commonly incorporated in the everyday practice. In addition, various polymers can be used for 3D printing [15]. Pre-surgical planning enables high precision, personalization, and improved clinical outcomes in oral rehabilitation and implantology [15].

The aim of this report is to present a case of vertical ridge augmentation using a xenogenic bone substitute material, covered with a magnesium barrier membrane and fixed with magnesium screws.

2. CASE PRESENTATION

A 49-year-old male patient visited the University Medical Dental Center for oral rehabilitation. No history of systemic disease was reported. On clinical examination, the patient presented with partial edentulism in regions 15-16, 24 and 36. The treatment plan approved by the patient involved placement of dental implants in the abovementioned regions. Due to extensive bone deficiency in the first quadrant seen on cone-beam computed tomography (CBCT) (Fig. 1), a two-stage approach was planned. The first phase included vertical bone augmentation in regions 15-16. In 4 months, the second phase would follow, involving maxillary sinus floor elevation (MSFE) with lateral approach and simultaneous placement of two dental implants.

Preparation for the first stage included exporting the stereolithographic (STL) file from CBCT into specialized software (Meshmixer, Autodesk, Inc.) and printing a 3D model of the patient's jaws. Afterwards, the defect was manually reconstructed on the model with composite resin (Fig. 2). The model was then autoclaved and a resorbable magnesium barrier membrane was tailored and adapted to the composite-augmented defect in sterile conditions.

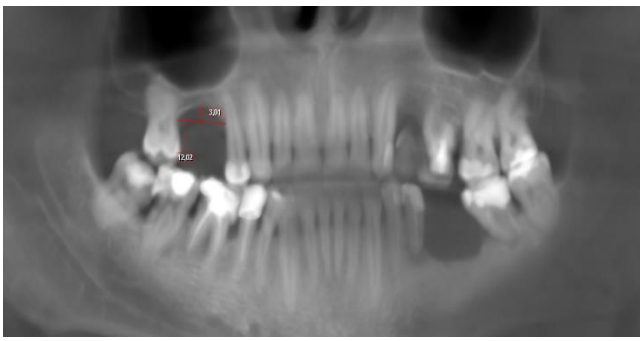

Fig. 1. Panoramic reconstruction from CBCT

The membrane was bent with special sculptor instruments, edges were rounded and 3 – 4 mm overlap of the membrane over the defect was designed, as per manufacturer's instructions.

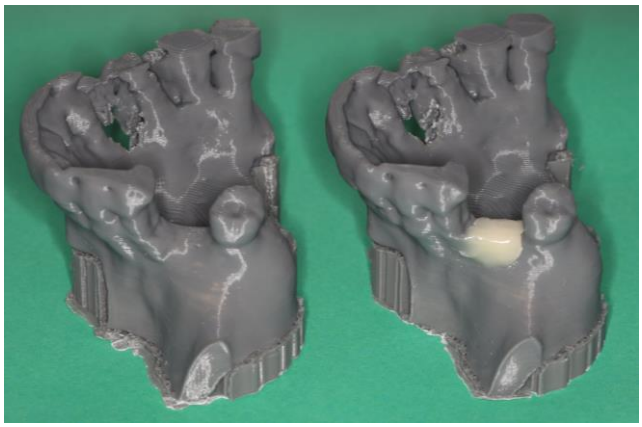

Fig. 2. 3D printed model of the defect (A) and reconstructed site with composite (B)

The surgical intervention was conducted under local anesthesia, after the patient had signed a declaration of informed consent. A triangular flap in the 13-17 region was reflected (Fig. 3).

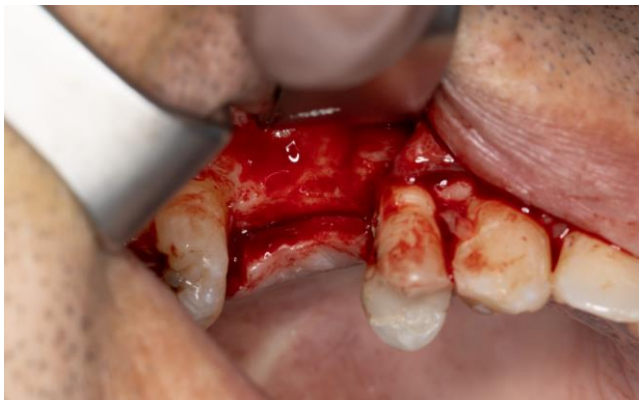

Fig. 3. Intraoral photo of the defect after flap elevation

The magnesium barrier membrane (NOVAMag®) was tested, perforated buccally and palatally for screw insertion (Fig. 4). Bone substitute material of bovine origin (Xenograft® 0.2 – 1.0 mm) was placed inside the membrane and onto the defect, according to the preoperatively composite-molded shape (Fig. 5). The membrane was finally adapted and fixed to the defect with resorbable magnesium screws (Fig. 6, Fig. 7 and Fig. 8). The flap was mobilized with a periosteal incision, adapted and sutured

tension-free with non-resorbable monofilament (Dafilon® 5/0) (Fig. 9). Hemostasis was achieved. No intraoperative complications occurred.

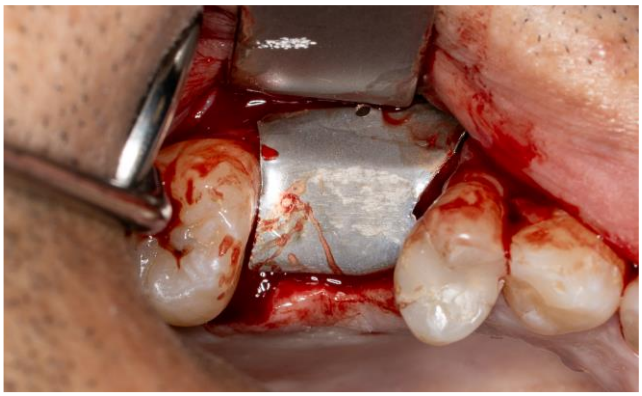

Fig. 4. Assessing the fit of the pre-formed magnesium membrane onto the defect

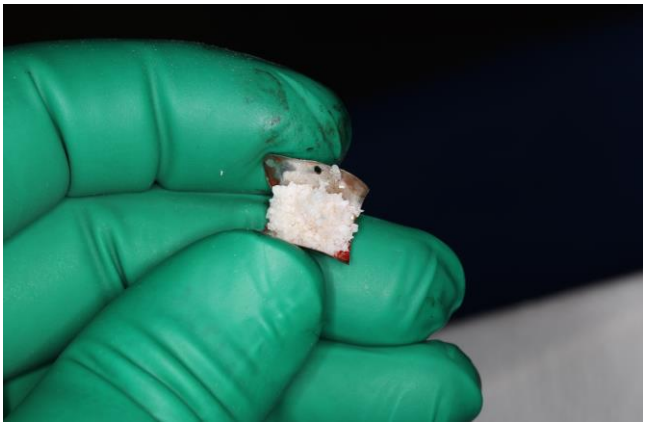

Fig. 5. Filling the membrane with xenograft prior to final placement and fixation

Fig. 6. Resorbable magnesium screw with insertion device

The patient was prescribed Amoxicillin every 8 hours for 5 days, as well as over-the-counter non-steroidal anti-inflammatory drugs. Post-operative and oral hygiene instructions were given. Sutures were removed after 2 weeks. No postoperative complications were observed. The second stage, consisting of MSFE with simultaneous placement of 2 implants, would be performed in the upcoming months. Ideally, 4 after the first stage, but the patient's schedule and work abroad will affect the intervention's timeframe.

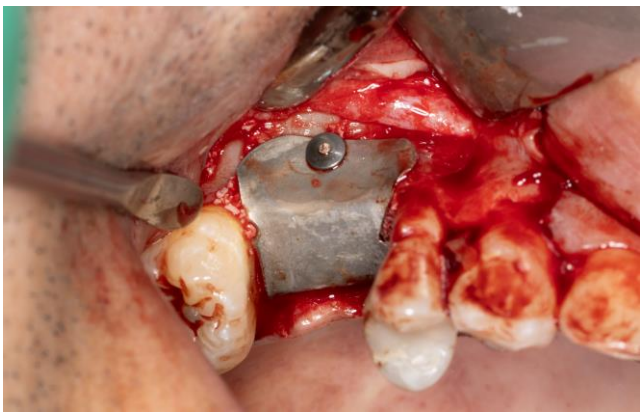

Fig. 7. Buccal view of the membrane filled with xenograft and stabilized with magnesium pins

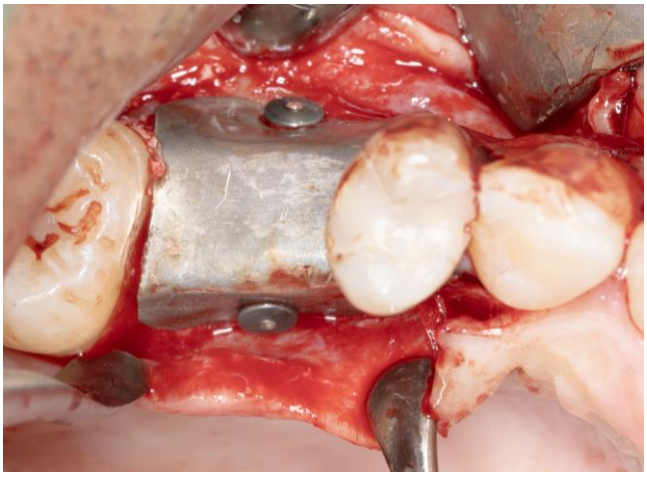

Fig. 8. Occlusal view of the membrane filled with xenograft and stabilized with magnesium pins

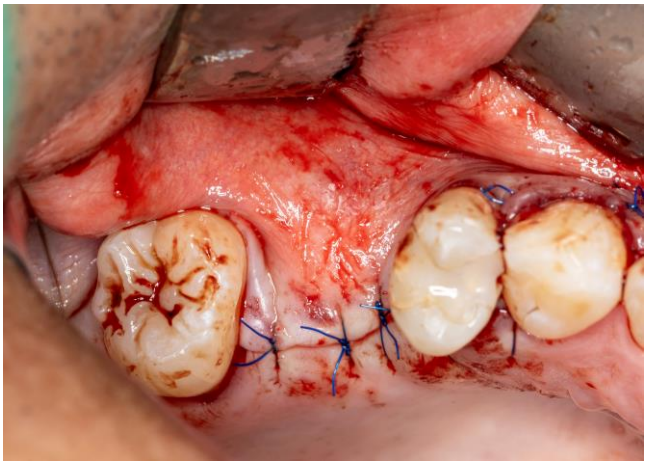

Fig. 9. Tension-free suturing of the flap after mobilization with the membrane completely covered

3. DISCUSSION

The choice of barrier membrane plays a crucial role in the success of guided bone regeneration procedures, with each type offering distinct advantages and limitations in achieving optimal outcomes for bone augmentation interventions.

Non-resorbable membranes made from titanium foil or polytetrafluorethylene (PTFE) are chemically inert and have

good biocompatibility. They maintain volumetric stability and provide excellent barrier function, but with one considerable drawback – the requirement of their removal at a second stage, which causes trauma to the patient, as well as marginal bone resorption due to periosteum detachment [7, 16]. In addition, complications such as exposure and subsequent infection can occur, compromising healing [7].

Resorbable membranes can be natural or synthetic in origin. Xenogenic collagen is the main natural compound, while synthetic materials include lactic and glycolic acid polymers and copolymers [17]. Their main advantage is resorbability – unlike non-resorbable membranes, a second stage surgery is not required for their removal. Collagen membranes have high biocompatibility due to their similarity to the human extracellular matrix. They support cell adhesion and proliferation, facilitating tissue regeneration [17, 18]. Drawbacks to collagen membranes, however, can be their unpredictable degradation rates, as well as lack of sufficient mechanical strength, potentially compromising the space maintenance required for effective bone regeneration [17, 18].

Synthetic polymers such as polylactic acid (PLA) and polyethylene glycol (PEG) are generally biocompatible, but may elicit inflammatory responses or degrade into acidic byproducts, potentially affecting the local tissue environment and hindering bone regeneration [7].

Compared to the traditional biomaterials for bone regeneration, magnesium products present some notable advantages, exhibiting excellent biocompatibility as they disintegrate into magnesium ions and non-toxic byproducts. They are reported to facilitate bone formation without eliciting adverse immune reactions [14].

Magnesium membranes are ductile. Owing to their malleability, they can be easily shaped, retaining the new configuration [19]. They are also rigid and can withstand masticatory forces, having mechanical properties comparable to human bone [18]. They are also stronger than collagen ones, due to the metal content, aiding in space maintenance [19]. Their stiffness resembles that of non-resorbable membranes, but without the need for a second-stage surgery, reducing patient morbidity.

Magnesium materials have been tested both in vitro and in vivo. Animal experiments have been conducted on mice, rats, rabbits, dogs and minipigs. Rider et al. studied the mechanical properties and biocompatibility of magnesium membranes in vitro and in vivo [17, 20]. The authors compared the physical properties of magnesium membranes to collagen ones in dog models, reporting similar outcomes histologically and histomorphometrically in terms of healing [17]. Degradation rate, measured by micro-CT, was also similar between the two [20]. The authors additionally evaluated corrosive properties on mini-pig models [17]. Based on their research it can be concluded that they provide optimal barrier function, volumetric stability and space maintenance for bone regeneration [17, 20, 21].

Magnesium has also been incorporated in resorbable pins for fixation of barrier membranes. These screws hinder membrane displacement and reduce micromovements to the graft, optimizing the healing process [17]. Their mechanical and biological properties have been studies in vitro and in vivo [21]. It has been demonstrated that these pins remain stable for 4 weeks post implantation, followed by variable resorption rates between the 4th and the 8th week [9]. Similar results have been reported when comparing magnesium and titanium screws in terms of membrane fixation and bone regeneration, based on histomorphometric parameters in dog models [21].

Magnesium membranes have various clinical implementations. These include treatment of maxillary sinus perforations after tooth extraction [19], as well as iatrogenic ones during maxillary sinus floor elevation with lateral approach [19], guided tissue and bone regeneration procedures [22 – 26]. A magnesium membrane has also been applied as a buccal shield, simultaneous with immediate implant placement [27]. The latter can be viewed as a modification of the bone block or the socket shield techniques.

In a case series by Elad et al. [19], maxillary sinus perforations were successfully closed with magnesium membranes and bone substitute materials - two perforations during tooth extraction and two during MSFE with lateral approach. Hangyasi et al. conducted regenerative periodontal therapy of infra-osseous bony pockets in 3 patients, filling the defects with xenografts and covering them with tailored magnesium membranes [22]. Blaskovic et al. presented cases of guided bone regeneration with simultaneous implant placement, both immediate and delayed [23, 24]. In all instances, magnesium membranes and bone substitute materials were used. Similarly, in another case series by Elad et al, buccal and palatal shields of magnesium foil were placed and filled with allograft, in conjunction with immediate implant placement [27]. Palkovics et al. performed guided bone regeneration with a magnesium membrane using a tunneling flap approach, but it was stabilized with titanium, rather than magnesium pins [25]. Further expanding the indications, Frosecchi et al. performed a ridge preservation procedure by applying a xenograft covered by the membrane in a large surgical defect after extraction of an impacted canine, followed by delayed implant placement [26].

All of the authors mentioned seem to be taking advantage of the membrane's ability to be pre-shaped to the dimensions of the defect, but they do so after flap elevation. In our case report, trimming and shaping was done preoperatively, on a 3D printed and augmented model in sterile conditions. 3D printed models with data from computed tomography (CT) or CBCT have been implemented in almost all surgical fields, among which are oral and maxillofacial surgery, as well as dental implantology [28, 29]. They allow for precise interpretation and analysis of the patient's anatomy and pathology [30]. In our case, this approach had several benefits, including the ability to optimally plan and execute the design of the membrane and its dimensions, as well as significantly reduce operating time, minimizing patient trauma. Reconstruction of the defect can be done digitally with specialized software, or manually on the 3D printed model, as presented here.

Surface modifications of magnesium membranes have been studied on various animal models. Steigmann et al. evaluated the biocompatibility and immune response to physical vapor deposition (PVD) coating versus uncoated magnesium membranes in mice [31]. Electrolytically and hydrothermally surface-treated magnesium meshes have

been tested on rat calvariae for the purposes of guided bone regeneration [18]. Barbeck et al. investigated the properties of magnesium meshes incorporated in collagen fleeces and treated with hydrofluoric acid (HF) [32], while Shan et al. studied magnesium surfaces with micro-arc oxidation (MAO), both in rabbit calvaria defects.

During degradation, magnesium membranes dissolve into magnesium salts and hydrogen gas, both of which undergo resorption [21]. Its byproducts completely degrade between the 8th and 16th week post implantation [20]. Resorption rates depend on whether pure magnesium or its alloys are used, if there are coverings or other modifications to the surface [12]. Pure magnesium degrades quicker than its alloys [33]. Magnesium ions, which are byproducts of membrane degradation, are associated with many physiological processes in the human body, at both intra- and extracellular level. They have positive effects for the function of the immune, cardiovascular, gastrointestinal, musculoskeletal, endocrine and nervous systems [34]. Moreover, pH alkalizes during dissolution of the compounds and release of ions, thereby reducing inflammation [19]. They are said to have certain antimicrobial properties, while also aiding in the differentiation of bone-forming cells [16].

Some authors mention a disadvantage of magnesium products used as medical devices – their low corrosion resistance. Upon degradation, as previously stated, they release hydrogen gas, which according to some could impair would healing, cause necrosis or emphysema [32]. According to other authors, however, gas cavities lead to a transient inflammatory reaction, after which they resorb and do not have significant clinical implications [20, 25]. Nonetheless, several surface modifications have been proposed, in order to minimize the potential negative effects of corrosion. These include calcium phosphate coating, passivation by plasma electrolytic oxidation (PEO), micro-arc oxidation (MAO), hydrothermal treatment (HT) or treatment with hydrofluoric acid (HF) [18, 32, 33].

With regard to limitations, the abovementioned hydrogen gas release, as well as rapid degradation rate and mechanical strength concerns have been mentioned [14]. Although promising, magnesium materials need further clinical evaluation and follow-up.

In our case report, the patient is to be reevaluated in the upcoming months.

4. CONCLUSIONS

Restoration of edentulous jaws with dental implants represents a significant advancement in oral rehabilitation, yet challenges still persist in managing extensive bone defects, with particular regard to vertical bone augmentation. This case report highlights the potential of magnesium-based materials, such as resorbable magnesium membranes and screws, in overcoming some of the limitations of traditional bone regeneration techniques. Magnesium's unique properties, biocompatibility, mechanical strength, and resorbability, make it a promising alternative to the currently established resorbable and non-resorbable membranes, addressing patient morbidity and the need for secondary surgeries.

Integration of pre-surgical 3D printing improves efficiency and precision, minimizing operative trauma and providing better outcomes. To the best of our knowledge, this is the first case report on guided bone regeneration using a pre-shaped magnesium membrane designed on a 3D-printed and augmented model. This approach demonstrates the potential for personalized implants to transform regenerative procedures in dental implantology.

While early data provides optimism, more studies are needed to solidify the long-term efficacy of magnesium-based materials. Advances in material science, in addition to personalized surgical planning, could revolutionize regenerative techniques, allowing for safer, more effective, and individualized solutions in complex cases, representing the future of bone regeneration and dental implantology.

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