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REVIEW ARTICLE

Techniques on vertical ridge augmentation: Indications and effectiveness

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1 | INTRODUCTION

An unavoidable series of events takes place after tooth extraction, sometimes ending up with vertical and horizontal ridge deficiencies.[1–5] Schropp et al[3] reported that 50% of the horizontal ridge dimension and approximately 0.7 mm of vertical volumetric changes, respectively, occurred within the first 3 months after extraction. In a systematic review, Van der Weijden et al[6] showed that, after all the resorptive events are over, a mean buccal-lingual/palatal dimension of 3.87 mm and a vertical reduction of 1.7 mm might preclude oral rehabilitation due to a dearth of support to obtain implant stability in an adequate position. Recent systematic reviews have further supported these findings.[7,8] As such, it can be very challenging for clinicians to place implants in these areas. These clinical difficulties might be overcome by shorter implant placements[9] or by performing bone augmentation[10,11] or tilted implants.[12]

The aforementioned techniques, although more minimally invasive, may carry some esthetic concerns that can be overcome with pink acrylics (ie, "pink esthetics"). On the other hand, vertical ridge augmentation still constitutes a challenge regardless of the approach/biomaterials and, along these lines, this will rely directly on the degree of vertical deficiency and the host's existing anatomy.[13] Autogenous bone blocks (BBs) have been demonstrated to reconstruct large vertical defects and achieve successful vertical bone gain. In a recent systematic review, it has been shown that a mean gain of 4.75 mm can be achieved.[14] In addition, early membrane exposure rate associated with block grafting was 12.5%.[15] The exposure rate of the membrane can increase to 33% when titanium mesh is used.[16] Furthermore, Ozaki and Buchman[17] tested the resorptive pattern of block grafts for bone augmentation and found out that, irrespective of the bone graft embryologic origin, there is an unavoidable graft resorption (15%-60%) that takes place immediately after grafting and that this may affect graft dimension during early and late healing.[15,18–20] Recently, allogeneic bone blocks without a barrier membrane have been used for vertical ridge augmentation and shown some promising results in terms of bone gain and implant survival; nevertheless, there is still a lack of long-term evidence supporting its utilization.[21] Therefore, clinicians examined other possibilities (ie, materials and techniques). This led to guided bone regeneration utilizing anorganic bovine bone in combination with autologous bone, which has been shown to be effective in vertical augmentation of atrophied maxillary ridges.[22–26] In order to predictably achieve successful bone augmentation, the principle of "primary wound closure, angiogenesis, clot stability, and space maintenance" should be followed.[27] As such, when performing vertical bone augmentation, space creation and its maintenance during healing are essential (as per guided bone regeneration biologic principles).[28] Nonresorbable titanium-reinforced barrier membrane fulfills the aforementioned criteria and has been suggested for large vertical bone augmentation. On the other hand, the use of blocks or distraction osteogenesis represent alternatives where the nature (or the use) of the barrier membrane may not be so pivotal, given that these strategies assist in creating and maintaining the space for de novo bone formation.[29] Therefore, the goal of this review is to describe the different approaches advocated for vertical ridge augmentation along with the indications and the evidence that support its use.

2 | TECHNIQUES ON VERTICAL RIDGE AUGMENTATION

2.1 | Guided bone regeneration

2.1.1 | Biological foundation

Guided bone regeneration has been broadly documented for the reconstruction of alveolar ridge defects simultaneously with or staged to implant placement. The term implies the use of barrier membranes with the goal of fulfilling the principle by "compartmentalization."[12] Initially, it was advocated for the repair of the periodontium,[12] although it was later used for implant site development.[30,31] In other words, the function of the barrier membrane aims to promote bone formation while acting as a passive barrier to preclude soft tissue ingrowth. Moreover, the effect of the barrier membrane has been further shown to promote bone formation, as it induces molecular and cellular events. Preclinical studies have demonstrated that the use of nonresorbable barrier membranes enhances the levels of Runx2-positive osteoprogenitor cells, osteocalcin, alkaline phosphatase, osteopontin, and sialoprotein.[32–34] In fact, early healing (day 7) displays inflammatory response, immune response, and an overexpression of Gene Ontology terms related to angiogenesis and cell cycle regulation. At day 15, a more complex cellular activity and cell metabolism is evident, where the bone formation processes were significantly overexpressed, with several genes encoding growth factors, enzyme activity, and extracellular matrix formation. At this stage, a negative regulation of the Wnt signaling pathway is noted.[35] Furthermore, this type of barrier membrane has been shown to promote the expression of tissue via increasing matrix metallopeptidases 2 and 9 along with interleukin-1 and -6.[33] Similarly, studies assessing the effect of resorbable (collagen-based) membranes on bone expression have noted that there is an increase in osteocalcin, cathepsin K, and receptor activator of nuclear factor kappa B.[34] In fact, it was shown that this type of membrane hosts different cell phenotypes that progressively secrete major bone-related growth factors, such as bone morphogenetic protein-2.[34] These findings, therefore, indicate that the principle of guided bone regeneration by means of using a barrier membrane does not only preclude the migration of fibroblasts from an area aimed at being populated by bone-forming cells but also that the membranes promote and orchestrate the healing events.

From a clinical perspective, the principles for guided bone regeneration can be described as follows:[27]

1. Primary wound closure, to promote aseptic healing. Passive closure leads the wound to heal with less re-epithelization, collagen formation, wound contraction, and remodeling while limiting the post-operative discomfort. This principle has proved critical in vertical ridge augmentation. In fact, dehiscences are the most common leading cause of postoperative infection.
2. Angiogenesis, to stimulate the formation of the blood clot and initial formation of the granulation tissue that will result in the formation of the mineralization of the woven bone and later lamellar bone. Indeed, de novo bone formation has been demonstrated to be linked with the formation of new vessels within the grafted area. This is the reason why corticotomies are suggested (intrabony marrow penetration) to allow the migration of the cells with angiogenic and osteogenic potential.
3. Space creation and maintenance, to guarantee the proliferation of the bone-forming cells. This principle is key in supracrestal bone defects, where vertical ridge augmentation is aimed at deficient ridges. This is supplied primarily by the nature of the barrier membrane. Resorbable membranes are prone to collapse, whereas nonresorbable membranes are more valid and effective at providing volume, particularly titanium-reinforced membranes. Other strategies/devices have been proposed to supply more stability to resorbable membranes, such as the use of meshes or screws.
4. Stability of the clot that provides cytokines, growth factors, and signaling molecules. Micromotion may lead to fibrous encapsulation of the graft resulting in a failure of the regenerative procedure.

2.1.2 | Technical note

Vertical ridge augmentation by means of guided bone regeneration is a very technique-sensitive procedure.[36] For reliable performance, space creation and maintenance are demanded through the use of a moldable barrier membrane in combination with a bone substitute capable of safely building up a robust biological structure mimicking native tissues and providing sufficient volume. Nonresorbable titanium-reinforced barrier membranes fulfill these criteria and have been suggested to achieve successful vertical ridge augmentation in large defects.[37,38] Consequently, in order to successfully achieve vertical ridge augmentation, flap design should account for the fact that primary tension-free closure will need to be reached over an increased dimension after the bone graft has been placed into the defect.[27] In this sense, previous surgical procedures, such as other regenerative attempts, might alter the integrity of the soft tissues. For instance, scarring of the periosteum impacts upon flap elasticity and can impair flap advancement to achieve tension-free primary wound closure.[39] Other anatomical factors that can influence the ability to advance the flap coronally are the depth of the vestibule and the severity of the alveolar defect. Therefore, different strategies have been outlined to overcome these drawbacks. Based on this, a few preoperative factors listed in Table 1 have to be identified and controlled.

Different therapeutic approaches have been proposed for vertical ridge augmentation by means of guided bone regeneration according to the anatomical region and the presence of critical factors. These are examined in the following.

Vertical ridge augmentation in anterior ridges

The following steps have been recommended for vertical ridge augmentation in anterior atrophic ridges (Figure 1):

TABLE 1 Critical factors to be assessed preoperatively to enhance the likelihood of success in vertical ridge augmentation

Critical factor	Rationale	Management
Systemic factors and deleterious habits	Systemic factors such as hyperglycemia and smoking may impair wound healing and increase the likelihood to postoperative infection	Smoking should be restricted 3 mo before vertical ridge augmentation. Other conditions must be further controlled
Defect morphology	Concave/contained defect configurations are rather more favorable than convex/uncontained defects	Assess defect characteristics to identify feasibility
Nature of the periosteum	The periosteum might be scarred in the case of previous regenerative attempts. This may alter flap elasticity and may impede the adequate coronal advancement to secure tension-free flap closure	Applying periosteoplasty or eliminating the damaged periosteum
Vestibular depth	Shallow vestibular depth may challenge the coronal advancement of the flap	Applying remote vertical releasing incisions and the safety flap
Presence of distal tooth (applicable in posterior ridges)	This may interfere with flap closure	Extraction of the distal molar and let the site heal spontaneously for ≥3 mo

1. Remote flap: This design consists of crestal and vertical releasing incisions. A full-thickness, midcrestal incision is typically used in the keratinized gingiva with a surgical scalpel (15C). For surgical access, the two divergent vertical incisions are placed at least one tooth away from the surgical site. The maximum distance of the vertical incisions is two teeth away from the defect. A larger flap will be easier to close and will result in less mucogingival distortion. A periosteal releasing incision must be carefully performed. In scenarios that exhibit shallow vestibule, a "suborbicularis preparation" should be carried to gain advancement from the coronal and lateral regions. Moreover, the periosteal releasing incision is different in scenarios that have scarred periosteum. In this case, a periosteoplasty or a partial excision of the periosteum should be performed.
2. Recipient site preparation: The recipient bone bed is prepared with multiple de-cortication screw holes using a small round bur to promote angiogenesis.
3. Membrane adaptation: A suitable-sized titanium-reinforced polytetrafluoroethylene membrane is selected and trimmed so that it completely covers the volume of the graft and its edges are not in contact with the natural teeth. Otherwise, a resorbable membrane with tenting screws is also a choice. Nevertheless, this is not advised in severely atrophic ridges.
4. Membrane fixation: Immobilization/stabilization of the membrane of the graft is the key to success. The membrane is stabilized first on the lingual/palatal sides using titanium pins.
5. Bone grafting: A mixture of autogenous graft and bone substitute is recommended. It must be placed into the defect and then the membrane is folded over and stabilized with additional titanium pins or screws.
6. The free curtain flap and papilla shift technique: Two vertical incisions are made two, three, or even four teeth away from the defect, depending on the severity of the vertical defect. After periosteal incisions and elastic fiber separation, the clinician can laterally position the remote areas of the flap and shift each papilla mesially in order to overcome the shortcomings of the shallow vestibule.
7. Flap closure: The flap must be sutured in two layers. The first layer is closed with horizontal mattress sutures placed 5 mm from the incision line, and then single interrupted sutures are used to close the edges of the flap.

Vertical ridge augmentation in posterior ridges

The following steps have been recommended for vertical ridge augmentation in the posterior atrophic ridges:

1. Safety flap: A full-thickness, midcrestal incision is used in the keratinized mucosa with a surgical scalpel (15C). The distal extension of the crestal incision ends within 2 mm of the retromolar pad. For surgical access, a distal oblique vertical incision is made toward the coronoid process of the mandible. A vertical incision is placed mesio-buccally at least one tooth away (preferably two) from the surgical site. Periosteal elevators are used to reflect a full-thickness flap beyond the mucogingival junction and at least 5 mm beyond the bone defect. A periosteal releasing incision must be performed at this stage. Periosteoplasty might be encouraged in the case that the periosteum is scarred.
2. Recipient site preparation: The recipient bone bed is prepared with multiple de-cortication screw holes using a small round bur to promote angiogenesis.
3. Membrane adaptation: A titanium-reinforced polytetrafluoroethylene membrane is selected and trimmed so that it totally covers the volume of the graft and the edges are not in contact with the natural teeth. Otherwise, a resorbable membrane with tenting screws is also a choice. Nevertheless, this is not advised in severely atrophic ridges.
4. Membrane fixation: Immobilization/stabilization of the membrane and the graft is the key to success. The membrane is stabilized first on the lingual/palatal sides using titanium pins. If the

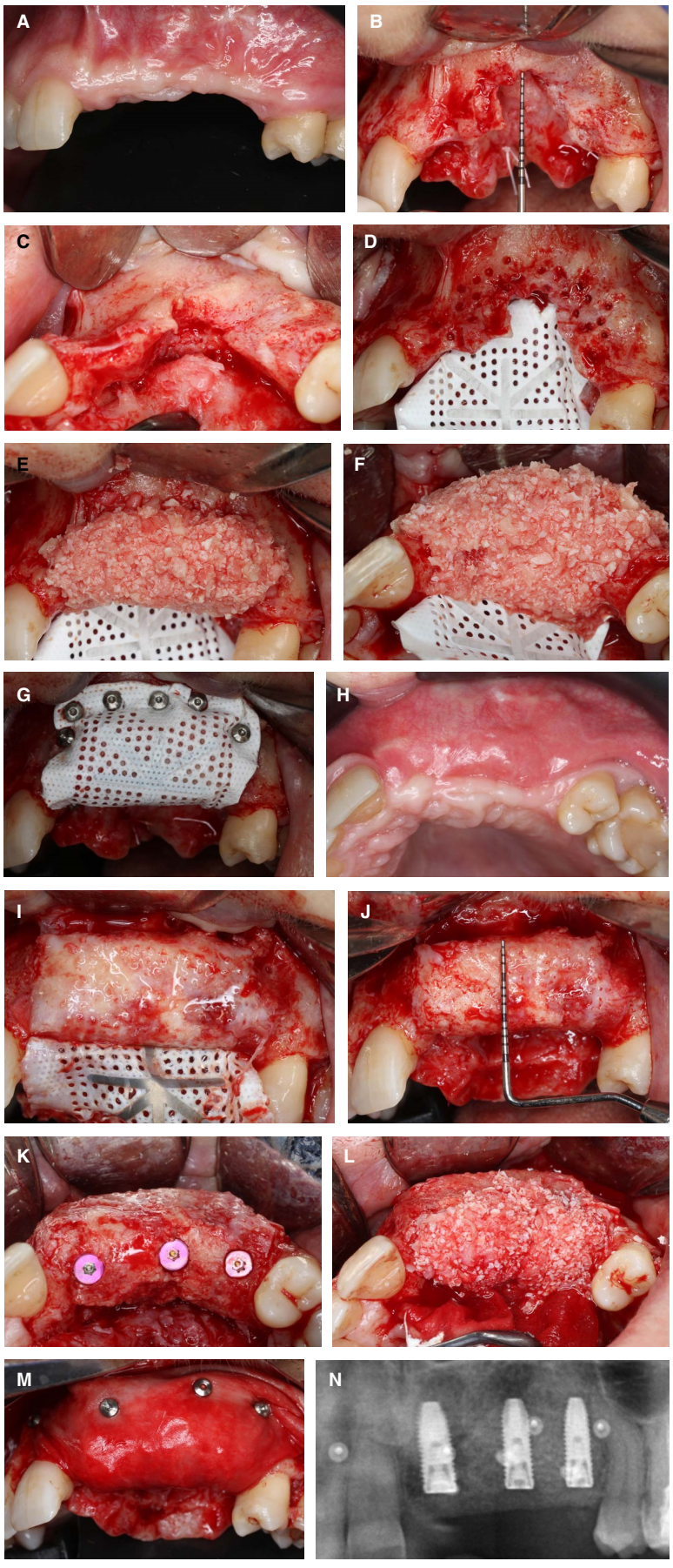

FIGURE 1 Representative case of an anterior maxillary vertical defect treated with guided bone regeneration. A, Labial view of an anterior maxillary defect after trauma. B, C, Labial and occlusal views of a severe vertical and horizontal ridge defect in the anterior maxilla after flap elevation. D, Labial view of a perforated polytetrafluoroethylene titanium-reinforced membrane fixated on the palate. E, F, Labial and occlusal views of a particulated bone graft consisting of a 60:40 ratio of autogenous particulated bone and anorganic bovine bone mineral. G, Labial view of the polytetrafluoroethylene membrane after fixation. H, Occlusal view of the site after 9 mo of uneventful healing. I, J, Labial views of the newly formed bone at membrane removal. K, Occlusal view of three implants placed into the regenerated bone. L, M, Occlusal and buccal views of a mini sausage, protecting layer of bone graft placed on the regenerated bone consisting of 70% anorganic bovine bone mineral and 30% autogenous bone. N, Panoramic radiograph demonstrating the implants placed into the regenerated bone.

placement of the first lingual pin is tricky, a "temporary pin" is placed on the crest just behind the last tooth.

5. Bone grafting: A mixture of autogenous graft and bone substitute is recommended to provide osteoinductive and osteoconductive properties in a ratio equal to or favoring autogenous bone. It must be placed into the defect and then the membrane is folded over and stabilized with additional titanium pins or screws.
6. Lingual flap advancement: The reason behind this flap design is based on the location of the attachment of the mylohyoid muscle and also on the protection of vital anatomical landmarks, such as the lingual nerve and the sublingual artery. Three maneuvers are encouraged based on three different zones (Figure 2):
   - *The first zone* is around the retromolar pad where the lingual nerve is running in close proximity. Tunneling and lifting on the retromolar pad is indicated.
   - *The second zone* is located in the molar region where the mylohyoid line is attached closer to the crest. Mylohyoid detachment by means of blunt dissection is indicated.
   - *The third zone* is the premolar region where the muscle is attached deep and there is a deep periosteal attachment of the soft tissue to the lingual side of the mandible. A horizontal hockey stick periosteal incision is indicated.
7. Flap closure: The flap must be sutured in two layers. The first layer is closed with horizontal mattress sutures placed 5 mm from the incision line, and then single interrupted sutures are used to close the edges of the flap.

Indications and limitations

The following indications can be advocated for guided bone regeneration:

1. Simultaneous grafting and implant placement. Simultaneous implant placement is possible when there is up to 4 mm of vertical bone deficiency when adequate bone width of the basal bone exists. Beyond 4 mm of vertical deficiency, a staged approach is recommended.[40]
2. Localized vertical deficiency of partially edentulous patients is the most frequent indication for guided bone regeneration. Edentulous patients can also be treated successfully; however, only a few articles addressed the details of this approach.

On the other hand, limitations for guided bone regeneration are as follows:

1. There is no defect height or length limitation of the utilization of guided bone regeneration. However, guided bone regeneration was originally utilized for defects involving one to three teeth defects. This has been evolved in the past decades; however, the extent of defect that can be regenerated is still a widely thought misconception.
2. Posterior mandibular vertical defects when the infra-alveolar nerve is exposed should not be treated with bone grafts placed directly on the exposed nerve, including guided bone regeneration.
3. Since the utilization of bone replacement materials such as allografts or xenografts has limited success in the reconstruction of vertical ridge defects, the utilization of at least 50% of autogenous bone chips is still indicated in most reconstructions. When guided bone regeneration is utilized, in most cases the source of bone is intra-oral. Therefore, the availability of autogenous intra-oral bone can be the main limitation of sites treated with guided bone regeneration.

2.1.3 | Effectiveness based on clinical studies

Several studies report on the effectiveness of guided bone regeneration in achieving vertical bone regeneration either in the maxilla or mandible (Table 2). A wide variety of surgical procedures have been reported in the literature, employing different barrier membranes, bone grafts, and space maintenance strategies that potentially impact on the outcome of the regenerative surgery. In addition, when interpreting the results from the literature, it is important to take into consideration not only the amount of regenerated bone but also the depth/dimensions of the original defect.

Most studies employed titanium-reinforced polytetrafluoroethylene membranes, which are considered ideal for this type of surgical procedure as they can provide a secluded space for a long time as well as prevent the collapse of the soft tissue inside the defect. In an early study, Simion et al[41] proved the efficacy of the titanium-reinforced expanded polytetrafluoroethylene membranes in a simultaneous approach, reporting mean vertical bone gains of 3.38 ± 0.81 mm (demineralized freeze-dried bone allograft group) and 4.16 ± 2.05 mm (autologous group), with the percentage regeneration being 132.6 ± 41.3% and 93.5 ± 21.9%, respectively. In another study by the same research group, expanded polytetrafluoroethylene membranes combined with simultaneous implant placement were able to regenerate 2.94 ± 1.15 mm (89.3 ± 64.2%), 3.27 ± 0.88 mm (130 ± 40.7%), and 3.95 ± 1.79 mm (116 ± 51%) of the defect when they were used without graft, in combination with demineralized freeze-dried bone allograft, or in combination with autologous graft, respectively.[26] Furthermore, nonresorbable membranes were used in combination with alloplastic materials,[42] xenografts,[43,44] allografts,[26,41,45,46] autologous grafts,[23,26,41,45–48] and combinations thereof[38,45,49–56] yielding similar results with percentage bone gain ranging between 62% and 139%. Regarding the time of implant placement, both simultaneous[23,26,38,41,42,44,45,48,52] and staged approaches[23,41,43,45–47,49–56] were shown to be effective in yielding vertical regeneration. However, a recent study of Urban et al[54] demonstrated that when using polytetrafluoroethylene membranes there is an increased probability of incomplete bone regeneration by 2.5 times for each millimeter of regeneration needed; hence, a simultaneous approach in a deep defect might result in an increased risk of implant dehiscence at the reentry.

Resorbable collagen membranes have also been employed in vertical regenerative procedures either alone[57] or in combination with space-maintenance strategies, such as tenting screws,[58,59]

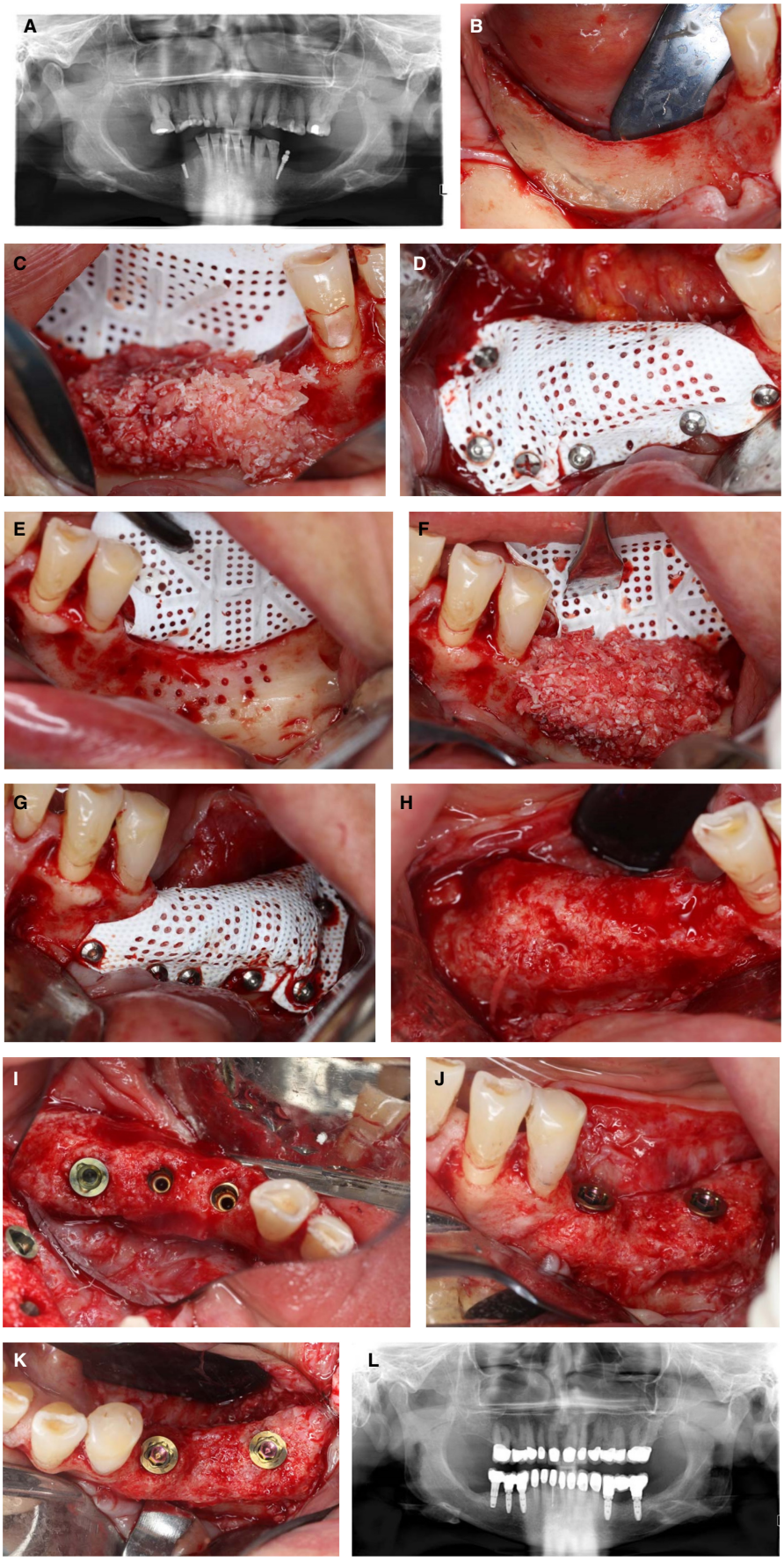

FIGURE 2 Representative case of a bilateral vertical and horizontal ridge defect in the posterior mandible. A, Panoramic radiograph demonstrating the posterior mandibular defects. B, E, Labial views demonstrating the vertical defect in addition to a knife-edge atrophy on the right side. C, F, Labial views of particulated bone graft consisting of a mixture of 1:1 ratio of autogenous bone and anorganic bovine bone mineral. D, G, Labial views of a perforated polytetrafluoroethylene titanium-reinforced membrane fixated. H-K, Labial and occlusal views of the regenerated bone at implant placement after 9 mo of uneventful healing. L, Panoramic radiograph demonstrating stable crestal bone after loading.

titanium mesh,[50,60–63] osteosynthesis plates,[48] and simultaneous implant placement.[48,50,57,58,64,65] In addition, they were used either in combination with alloplastic material[57] or xenograft[57,64] or allograft[58,59] or autogenous bone or mixed grafts.[50,58,60,62,63] Their amount of regenerated bone ranges from 25% to 92.9% and from 35% to 102% for the native[48,57,61,63,64] and cross-linked[50,57,58,60,62,65] collagen membrane, respectively. Consistently, a recent systematic review[66] found that the mean vertical bone gain for nonresorbable, resorbable cross-linked, and native collagen membranes was on average 4.42 mm (95% confidence interval 3.97-4.87 mm), 4.19 mm (95% confidence interval 3.18-5.21 mm), and 2.66 mm (95% confidence interval 1.49-3.82 mm), respectively.

2.1.4 | Postoperative complications

Postoperative complications during the healing period, such as membrane exposure and abscess, are potentially able to significantly affect the outcome in terms of bone regeneration. Nevertheless, even though the occurrence of membrane exposure is rather frequent (approximately 12%), the percentages of failures reported in the literature are low.[26,41,43,45,46,48,50,54,55,58–60,63,65,66] Simion et al,[26] using expanded polytetrafluoroethylene membranes, achieved regenerations of roughly 57% and 128% of the original defect in exposed and nonexposed sites, respectively. Similarly, Beitlitum et al,[58] using a cross-linked collagen membrane, found that membrane exposure led to approximately 50% less bone regeneration. In a recent study, the exposure of the native collagen membrane supported by a customized titanium mesh led to a resorption of approximately 1 mm more in comparison with nonexposed sites.[63]

2.1.5 | Long-term predictability

Long-term predictability of vertical ridge augmentation is monitored by measuring the marginal bone loss around dental implants. It is generally accepted that implants might experience an early marginal bone remodeling as a result of the formation of the biologic width,[67,68] and a large number of factors have been suggested to affect bone remodeling at this stage, including implant- and prosthetic-related and patient-based factors.[69–75] Apropos the stability of the marginal bone level after the first year, Albrektsson et al[76] proposed that successful implants register an annual marginal bone loss of less than 0.2 mm; yet, in the modern implant dentistry, progressive marginal bone loss around dental implants is no longer acceptable as it is considered a sign of peri-implantitis.[77] Hence, it seems reasonable to wonder whether implants placed in regenerated bone are more prone to experience bone loss in comparison with those that are located in pristine bone structure.

Data regarding the long-term stability of the peri-implant bone are rather scarce in literature and mainly coming from retrospective case series[23,26,37,42–45,48,50,55,63,65,78,79] (Table 2). Concerning nonresorbable membrane, most short-term studies (up to 12 months) report a mean marginal bone loss up to approximately 1 mm during the first year of loading.[23,43,45,55,78,79] A preclinical trial suggested that, after membrane removal, bone is subjected to resorption.[80] These results can be also partially explained by the type of implants employed (Brånemark implants) and the incomplete bone regeneration at certain implants that were placed simultaneously with the vertical guided bone regeneration.[26,81] After the first year, studies consistently showed stability of the peri-implant bone.[23,26,37,42,44,45,78] Merli et al,[42] in a randomized controlled trial with follow-up up to 6 years, showed a bone loss of 0.59 mm, 0.53 mm, and 0.49 mm in comparison with baseline values at 1 year, 3 years, and 6 years, respectively. Another prospective case series found that the marginal bone loss at 2 years (0.98 ± 0.42 mm) was comparable to 1-year results (0.90 ± 0.60 mm).

In relation to resorbable membranes, Llambes et al,[65] in a 12-month prospective study, reported a marginal bone loss of 1.36 ± 0.77 mm around implants placed simultaneously with a vertical bone regeneration performed with cross-linked collagen membrane and xenograft. In addition, two randomized controlled trials failed to find statistically significant differences in terms of vertical ridge augmentation between polytetrafluoroethylene membranes and resorbable membranes supported by osteosynthesis plates[78] and titanium meshes.[79] Recently, a retrospective case series reported a marginal bone loss of roughly 0.5 mm after 12 months of implants after (a staged approach) guided bone regeneration was conducted with native collagen membrane supported by a titanium mesh.[63] The randomized controlled trial of Merli et al,[37,78] is the only study reporting results beyond 12 months on the marginal bone level of implants placed following vertical guided bone regeneration conducted with resorbable membranes. These findings showed a bone remodeling of 0.55 mm and 0.58 mm after 3 years and 6 years, respectively, and the results were comparable to those of nonresorbable membranes.

All in all, the current literature suggests that an average bone loss of about 1 mm is expected after the first year of loading and a substantial stability of the marginal bone level could be assumed after this period. Nonetheless, it should be taken into account that only low-quality data are available due to the extreme heterogeneity of the surgical techniques employed, the poor study design of most studies, and the high percentage of patient dropout in trials with follow-up greater than 12 months.

2.2 | Block grafting: Onlay, inlay, and cortical plates

2.2.1 | Biological foundation

Grafting with a bone block is a versatile and well-documented procedure for the treatment of alveolar ridge defects in a broad range of clinical scenarios.[82,83]

Onlay grafting represents the most conventional approach inherited from reconstructive procedures in orthopedic and craniomaxillofacial surgery and consists of the rigid fixation of a bone block directly over a recipient site.[84]

TABLE 2 Studies reporting on the effectiveness and long-term stability of vertical ridge augmentation by means of guided bone regeneration

Authors (y)	Study design	Patients/sites/implants	Follow-up after functional loading (mo)	Surgical technique	Location	Vertical bone gain at site level, mean ± SD (mm)				
						Mean bone gain/Mean bone defect (%)	Membrane exposure rate, patients/sites (%)	Abscess/infection rate, patient/sites (%)	Failure rate, patients/sites[a] (%)	Marginal bone loss (mm)
Chiapasco et al (2004)[81]	Randomized controlled trial (parallel)	Test 1: 6/6/13 Test 2: 5/5/12	12-36	Test: Expanded polytetrafluoroethylene titanium-reinforced membrane) + autologous (1: simultaneous; 2: staged Control: Intra-oral distractor	Maxilla and mandible	Test 1: Not reported Test 2: Not reported	Test 1: 33.3/33.3 Test 2: 20/20	Test 1: 16.6/16.6 Test 2: 0/0	Test 1: 0/0 Test 2: 0/0	*Baseline* Test 1: 1.27 ± 0.8 Test 2: 0.69 ± 0.3 *1 y* Test 1: 1.83 ± 1.0 Test 2: 1.29 ± 0.4 *3 y* Test 1: 2.06 ± 0.9 Test 2: 1.69 ± 0.3
Abrahamsson et al (2012)[61]	Randomized controlled trial (parallel)	Test: 10/10/10	Only reentry	Test: Soft tissue expander + autologous + titanium mesh + native collagen resorbable membrane (staged) Control: Autologous graft (staged)	Single or partial anterior maxilla	Test: 3.0 ± 1.4 Test: 73.1 ± 34.1	Test: 20/20	Test:0/0	Test:0/0	Not reported
Beitlitum et al (2010)[58]	Controlled clinical trial	23/23/51	Only reentry	Test: Autologous bone + freeze-dried bone allograft + cross-linked resorbable membrane (staged or simultaneous) Control: Freeze-dried bone allograft + cross-linked resorbable membrane (staged or simultaneous)	Single or partial anterior or posterior maxilla or mandible	Test: 3.5 ± 1.2 Control: 3.47 ± 1.25 Test: 35.9 Control: 63.4	Test: 25/25 Control: 33.3/33.3	Test: 0 Control: 0	Test: 0 Control: 0	Not reported
Canullo and Malagnino (2008)[44]	Case series (retrospective)	10/10/24	36 (24-54)	Expanded polytetrafluoroethylene titanium-reinforced membrane + xenograft (simultaneous)	Partial anterior or posterior maxilla or mandible	5.4 ± 1.5 106 ± 18	10/10	0/0	0/0	1.4 ± 0.4
Canullo and Sisti (2010)[42]	Case series (prospective)	20/20/42	24	Expanded polytetrafluoroethylene titanium-reinforced membrane + magnesium-enriched hydroxyapatite (simultaneous)	Single or partial anterior or posterior maxilla or mandible	5.85 ± 1.48 139.6 ± 23.5	5/5	0/0	0/0	1 y: 0.90 ± 0.60 2 y: 0.98 ± 0.42

TABLE 2 (Continued)

Authors (y)	Study design	Patients/sites/implants	Follow-up after functional loading (mo)	Surgical technique	Location	Vertical bone gain at site level, mean ± SD (mm)	Membrane exposure rate, patients/sites (%)	Abscess/infection rate, patient/sites (%)	Failure rate, patients/sites[a] (%)	Marginal bone loss (mm)
						Mean bone gain/ Mean bone defect (%)				
Cardaropoli et al (2013)[64]	Case series (prospective)	20/20/35	Only reentry	Xenograft + fibrin-fibronectin sealing + native collagen resorbable membrane (simultaneous)	Single or partial anterior or posterior maxilla or mandible	3.95 ± 1.47 92.9	0/0	0/0	0/0	Not reported
Chiapasco et al (2021)[63]	Case series (retrospective)	41/53/106	12	Custom-made titanium mesh + autogenous + xenograft 1:1 + native collagen membrane (staged)	Maxilla or mandible	4.39 (patient level) 8.09 ± 12.27 (vertical bone resorption at reentry)	Not reported/20.8	Not reported/1.9	Not reported/1.9	6 mo (24 patients): 0.33 ± 0.34 mesial; 0.37 ± 0.41 distal 12 mo (13 patients): 0.54 ± 0.34 mesial; 0.56 ± 0.42 distal
Cucchi et al (2017, 2021)[50,79]	Randomized controlled trial (parallel)	40/40/99	12	Test: Allograft + autologous (1:1) + titanium mesh + cross-linked collagen membrane (simultaneous) Control: Allograft + autologous (1:1) + high-density polytetrafluoroethylene titanium-reinforced membrane (simultaneous)	Partial posterior mandible	Test: 4.1 ± 1 Control: 4.2 ± 1 Test: 102.5 Control: 105	Test: 15.7/15.7 Control: 10/10	Test: 10.5/10.5 Control: 10/10	Test: 5.2/5.2 Control: 10/10	*Baseline* Test: −0.01 ± 0.75 Control: 0.27 ± 0.76 *1 y* Test: 0.66 ± 0.80 Control: 0.89 ± 0.75
Cucchi et al (2021)[62]	Randomized controlled trial (parallel)	Test: 15/30/34 Control: 15/30/37	Till implant osteointegration	Test: Custom-made titanium mesh + autogenous + xenograft 1:1 (staged) Control: Custom-made titanium mesh + autogenous + xenograft 1:1 + cross-linked collagen membrane (staged)	Maxilla or mandible	Test: 4.74 ± 2.56 Control: 6.36 ± 2.31 Test: 74.32 ± 22.10 Control: 82.30 ± 17.98	Healing complications Test: 33.3/16.7 Control: 13.3/6.7		Test: 0/0 Control: 0/0	Not reported

(Continues)

TABLE 2 (Continued)

Authors (y)	Study design	Patients/sites/implants	Follow-up after functional loading (mo)	Surgical technique	Location	Vertical bone gain at site level, mean ± SD (mm)	Membrane exposure rate, patients/sites (%)	Abscess/infection rate, patient/sites (%)	Failure rate, patients/sites[a] (%)	Marginal bone loss (mm)
						Mean bone gain/Mean bone defect (%)				
Fontana et al (2008)[46]	Randomized controlled trial (parallel)	5/10/25	24 (12-36)	Test: Expanded polytetrafluoroethylene titanium-reinforced membrane + allograft (staged) Control: Expanded polytetrafluoroethylene titanium-reinforced membrane + autologous (staged)	Partial posterior mandible	Test: 4.7 ± 0.48 Control: 4.1 ± 0.88 Test: 91.3 ± 7.5 Control: 85.8 ± 20.5	Test: 0/0 Control: 0/0	Test: 0/0 Control: 20/20	Test: 0/0 Control: 0/0	Not reported
Fontana et al (2015)[45]	Case series (retrospective)	21/29/75	42 (12-72)	Autologous only, allograft only or xenograft + autologous 1:1 + expanded polytetrafluoroethylene titanium-reinforced membrane (staged or simultaneous)	Partial posterior mandible	4.15 ± 1.34 90.1 ± 11.8	14.3/10.3	9.5/6.9	0/0	1 y: 0.64 ± 0.72 3 y: 1.34 ± 1.26 6 y: 0.91 ± 0.74
Funato et al (2013)[60]	Case series (retrospective)	19/19/not reported	Only reentry	Autologous + xenograft + cross-linked resorbable membrane + recombinant human platelet–derived growth factor + titanium mesh (staged)	Partial anterior or posterior maxilla or mandible	8.6 ± 4 85.8 ± 25.6	11.8/11.8	0/0	0/0	Not reported
Ji et al (2021)[55]	Case series (prospective)	14/26/24	12	Titanium-reinforced microporous expanded polytetrafluoroethylene membrane + allograft and xenograft 1:1 or 2:1 (staged)	Posterior maxilla or mandible	5.9 ± 2.7 63.4	Not reported/23.1	0/0	Not reported/not reported	Mesial: 0.16 ± 0.05 Distal: 0.15 ± 0.04
Lee et al (2022)[57]	Case series (retrospective)	22/22/not reported	1-7 y (after guided bone regeneration treatment)	Xenograft or alloplastic material + native collagen membrane or cross-linked collagen membrane (simultaneous or staged)	Maxilla or mandible	5.78 ± 1.72 85.6	9.1/9.1	0/0	0/0	No marginal bone loss noted during the follow-up period

TABLE 2 (Continued)

Authors (y)	Study design	Patients/sites/implants	Follow-up after functional loading (mo)	Surgical technique	Location	Vertical bone gain at site level, mean ± SD (mm)	Membrane exposure rate, patients/sites (%)	Abscess/infection rate, patient/sites (%)	Failure rate, patients/sites[a] (%)	Marginal bone loss (mm)
						Mean bone gain/ Mean bone defect (%)				
Leong et al (2015)[59]	Randomized controlled trial (parallel)	16/19/not reported	Only reentry	Test: Allograft + native collagen resorbable membrane (staged) Control: Cancellous and cortical allograft + native collagen resorbable membrane (staged)	Partial posterior mandible	Test: 1.78 ± 2.3 Control: 1 ± 2.2 Test: 44 Control: 25	Test: Not reported/77.8 Control: Not reported/30	Test: 0/0 Control: 0/0	Test: 0/0 Control: 0/0	Not reported
Llambes et al (2007)[65]	Case series (prospective)	11/13/32	12	Autologous + xenograft + cross-linked collagen resorbable membrane (simultaneous)	Partial posterior mandible	2.95 ± 1.21 81.1 ± 29.0	18.2/15.38	0/0	9.1/7.7	1.36 ± 0.77
Maiorana et al (2021)[56]	Randomized controlled trial (split-mouth)	Test: 5/5/11 Control: 5/5/10	Till implant osteointegration	Test: High-density polytetrafluoroethylene membrane + tenting screws + autogenous + xenograft 1:1 (staged) Control: Titanium mesh + tenting screws + autogenous + xenograft 1:1 (staged)	Posterior mandible	Test: 4.2 ± 2.2 Control: 1.5 ± 1.6 Test: 100 Control: 44.1	Test: 0/0 Control: 0/0	Test: 0/0 Control: 0/0	Test: 0/0 Control: 0/0	Not reported
Mendoza-Azpur et al (2018)[51]	Case series (retrospective)	35/not reported/not reported	Only reentry	High-density polytetrafluoroethylene titanium-reinforced membrane + autologous + xenograft 50:50 + tenting screws (staged)	Posterior maxilla or mandible	5.44 Not reported	26/not reported	0/0	0/0	Not reported

(Continues)

TABLE 2 (Continued)

Authors (y)	Study design	Patients/sites/implants	Follow-up after functional loading (mo)	Surgical technique	Location	Vertical bone gain at site level, mean ± SD (mm)	Membrane exposure rate, patients/sites (%)	Abscess/infection rate, patient/sites (%)	Failure rate, patients/sites[a] (%)	Marginal bone loss (mm)
						Mean bone gain/Mean bone defect (%)				
Merli etal(2014,2010, 2007)[37,48,78]	Randomized controlled trial (parallel)	22/22/77	72	Test: Native collagen resorbable membrane supported by osteosynthesis plates + autologous (simultaneous) Control: Expanded polytetrafluoroethylene titanium-reinforced membrane + autologous (simultaneous)	Single or partial anterior or posterior maxilla or mandible	Test: 2.16 ± 1.51 Control: 2.48 ± 1.13 Test: 73.7 Control: 90.8	Test: 9.1/9.1 Control: 9.1/9.1	Test: 18.2/18.2 Control: 9.1/9.1	Test: 18.2/18.2 Control: 9.1/9.1	*Baseline* Test: 0.75 ± 1.07 Control: 0.54 ± 0.67 *1 y* Test: 0.93 ± 0.34 Control: 1.03 ± 1.16 *3 y* Test: 1.30 ± 0.82 Control: 1.07 ± 0.90 *6 y* Test: 1.33 ± 0.83 Control: 1.00 ± 0.97 (10 sites)
Rocchietta et al (2016)[47]	Controlled clinical trial	10/12/not reported	Only reentry	Test: Autologous block graft + expanded polytetrafluoroethylene titanium-reinforced membrane (staged) Control: Autologous particulate graft + expanded polytetrafluoroethylene titanium-reinforced membrane (staged)	Partial posterior mandible	Test: 2.91 ± 0.92 Control: 4.45 ± 0.85 Test: 98 ± 4.6 Control: 92 ± 9.3	Test: 0/0 Control: 0/0	Test: 0/0 Control: 0/0	Test: 0/0 Control: 0/0	Not reported
Ronda et al (2014)[38]	Randomized controlled trial (parallel)	23/26/38	(15-37) from the membrane removal	Test: High-density polytetrafluoroethylene titanium-reinforced membrane + autologous + allograft 50:50 (simultaneous) Control: Expanded polytetrafluoroethylene titanium-reinforced membrane + autologous + allograft 50:50 (simultaneous)	Partial posterior mandible	Test: 5.02 ± 0.87 Control: 4.49 ± 0.68 Test: 120% ± 25% Control: 136% ± 46.5%	Test: 0/0 Control: 0/0	Test: 0/0 Control: 0/0	Test: 0/0 Control: 0/0	Not reported

TABLE 2 (Continued)

Authors (y)	Study design	Patients/sites/implants	Follow-up after functional loading (mo)	Surgical technique	Location	Vertical bone gain at site level, mean ± SD (mm)	Membrane exposure rate, patients/sites (%)	Abscess/infection rate, patient/sites (%)	Failure rate, patients/sites[a] (%)	Marginal bone loss (mm)
						Mean bone gain/Mean bone defect (%)				
Simion et al (1998)[41]	Controlled clinical trial	20/22/26	Only reentry	Test: Expanded polytetrafluoroethylene titanium-reinforced membrane + demineralized freeze-dried bone allograft (simultaneous) Control: Expanded polytetrafluoroethylene titanium-reinforced membrane + Autologous + (staged and simultaneous)	Partial anterior or posterior maxilla or mandible	Test: 3.38 ± 0.81 Control: 4.16 ± 2.05 Test: 132.6 ± 41.3 Control: 93.5 ± 21.9	Test: 20/20 Control: 10/8.3	Test: 0/0 Control: 10/8.3	Test: 0/0 Control: 0/0	Not reported
Simion et al (2001)[26]	Case series (retrospective) 3 arms	49/54/123 Test 1: 6/7/17 Test 2: 11/11/24 Test 3: 32/36/82	(16-69)	Expanded polytetrafluoroethylene titanium-reinforced membrane + Test 1 (blood clot), or Test 2 (demineralized freeze-dried bone allograft), or Test 3 (autologous) (simultaneous)	Partial anterior or posterior maxilla or mandible	Test 1: 2.94 ± 1.15 Test 2: 3.27 ± 0.88 Test 3: 3.95 ± 1.79 Test 1: 89.3 ± 64.2 Test 2: 130 ± 40.7 Test 3: 116 ± 51	Test 1: 0/0 Test 2: 18.2/18.2 Test 3: 12.5/11.1	Test 1: 14.3/16.6 Test 2: 0/0 Test 3: 3.1/2.9	Test 1: 0 Test 2: 0 Test 3: 0	*Baseline* Test 1: 1.29 ± 2.14 Test 2: −0.41 ± 0.95 Test 3: −0.36 ± 1.41 *1 y* Test 1: 2.64 ± 1.99 Test 2: 1.45 ± 0.56 Test 3: 1.34 ± 0.95 *3 y* Test 1: 2.64 ± 1.99 Test 2: 1.40 ± 0.57 Test 3: 1.27 ± 0.82
Todisco (2010)[43]	Case series (prospective)	20/25/64	12	Expanded polytetrafluoroethylene titanium-reinforced membrane + xenograft (staged)	Single or partial anterior or posterior maxilla or mandible	5.24 ± 1.5 96.8 ± 17.7	10/8	0/0	10/8 Intervention was repeated after 2 mo without complications	0.95 ± 0.21

(Continues)

TABLE 2 (Continued)

Authors (y)	Study design	Patients/sites/implants	Follow-up after functional loading (mo)	Surgical technique	Location	Vertical bone gain at site level, mean ± SD (mm)	Membrane exposure rate, patients/sites (%)	Abscess/infection rate, patient/sites (%)	Failure rate, patients/sites[a] (%)	Marginal bone loss (mm)
						Mean bone gain/ Mean bone defect (%)				
Urban et al (2009)[23]	Case series (retrospective)	35/36/82	40.3 (12-72)	Expanded polytetrafluoroethylene titanium-reinforced membrane + autologous bone (staged or simultaneous)	Full, single or partial anterior or posterior maxilla or mandible	5.5 ± 2.29 Not reported	0/0	2.9/2.7	0/0	1 y 1.01 ± 0.57 No further bone loss during study period
Urban et al (2014)[49]	Case series (prospective)	19/20/not reported	Only reentry	High-density polytetrafluoroethylene titanium-reinforced membrane + autologous bone chips + xenograft (1:1) (staged)	Partial anterior or posterior maxilla or mandible	5.45 ± 1.93 Not reported	0/0	0/0	0/0	Not reported
Urban et al (2021)[54]	Case series (retrospective)	57/65/not reported	Only re-entry	Titanium-reinforced polytetrafluoroethylene mesh + autologous + xenograft 1:1 + native resorbable collagen membrane (staged)	Maxilla or mandible	5.2 ± 2.4 96.5 ± 13.9	1.75/1.5	1.75/1.5	1.75/1.5	Not reported
Amaral Valladão et al (2020)[53]	Case series (retrospective)	8/23/not reported	1-7 y (after guided bone regeneration treatment)	High-density polytetrafluoroethylene titanium-reinforced membrane + autologous + xenograft 1:1 + injectable platelet-rich fibrin to agglutinate the graft + leukocyte and platelet-rich fibrin covering the high-density polytetrafluoroethylene membrane (staged)	Maxilla or mandible	5.6 ± 2.6 62.2	0/0	0/0	0/0	Not reported

TABLE 2 (Continued)

Authors (y)	Study design	Patients/sites/implants	Follow-up after functional loading (mo)	Surgical technique	Location	Vertical bone gain at site level, mean ± SD (mm)		Membrane exposure rate, patients/sites (%)	Abscess/infection rate, patient/sites (%)	Failure rate, patients/sites[a] (%)	Marginal bone loss (mm)
						Mean bone gain/ Mean bone defect (%)					
Windisch et al (2021)[52]	Case series (prospective)	19/24/45	Only reentry	High-density polytetrafluoroethylene titanium-reinforced membrane + autologous + xenograft 50:50 (simultaneous and staged)	Maxilla or mandible	Simultaneous group: 3.2 ± 1.9 Staged group: 4.5 ± 2.2	Simultaneous group: Not reported Staged group: Not reported	5.2/3.8	0/0	0/0	Not reported

Abbreviations: C, control; CCT, controlled clinical trial; DFDBA, demineralized freeze-dried bone allograft; FDBA, freeze dried bone allograft; GBR, guided bone regeneration; NR, not reported; Prosp, prospective; PTFE-d, expanded polytetrafluoroethylene; PTFE-e, dense polytetrafluoroethylene; RCT, randomized clinical trial; Ret, retrospective; rhPDGF, recombinant human platelet-derived growth factor; T, test.

[a]Complete graft removal/no implant could be placed in the regeneration site.

These grafts heal through an orchestration of cellular, vascular, and architectural events, which have been described in different preclinical models.[85–87] In the early stages of healing (3-5 days), nutrients are provided to the bone block exclusively by plasmatic circulation. Subsequently, micro-angiogenesis begins through the sprouting of capillaries from the surrounding soft tissues and the recipient site edges, which start to penetrate the graft. At 2 weeks, a strong inflammatory and vascular response is present with bone remodeling, micro-angiogenesis, and hypervascularization of the surrounding tissues; at 4 weeks, considerable remodeling is present, with formation of osteoid and an increase in the size and dimensions of the micro vessels penetrating the graft. Finally, complete graft revascularization is achieved at 8 weeks; and at 16 weeks, demarcation from the recipient site disappears and newly formed, relatively mature bone is present with no residual inflammatory cells.[85–88]

Similar to what has been described for guided bone regeneration,[27] the healing process of bone block grafts is based upon the following principles:

1. Primary wound closure, to promote aseptic healing without graft contamination.
2. Angiogenesis, to allow the graft revascularization by sprouting capillaries projecting toward the medullar aspect of the graft.
3. Space creation and maintenance from the bone block, which allows the proliferation of bone-forming cells during healing. Owing to the solid nature of bone block, space is created by the graft and no further device for space creation is required.
4. Stability of the blood clot provided by the structural integrity of the bone block and its rigid fixation to the recipient bed.

Furthermore, bone block grafting relies on the direct provision of bone-forming cells into the defect, when the bone graft has an autogenous origin, which represents the gold standard in vertical bone augmentations for its osteogenic, osteo-inductive, and osteoconductive properties.[82,89] In such a case, the osteogenic capacity of the graft is dependent upon the number of living bone cells that survive the early phases of healing, when nourishment is provided to the graft through plasmatic circulation from the surrounding tissues.[86]

It must be noted that bone block grafting does not rely on the principles of compartmentalization and cell exclusion as, in the majority of cases, no barrier membranes are required to avoid soft tissue infiltration or to provide further mechanical stability to the grafted area.[90] Indeed, some researchers advocate the direct contact of the bone block with the surrounding soft tissues as a means to promote graft nourishment and micro-angiogenesis during the early stages of healing, especially when using bone block grafts with a high cortical composition.[91,92]

In fact, bone blocks with intramembranous origin (skull and mandible), presenting a predominant cortical composition, were reported to have greater volumetric stability and scaffolding effect but poorer osteogenic and angiogenetic capacities than bone blocks with endochondral origin (rib, iliac crest), presenting a higher

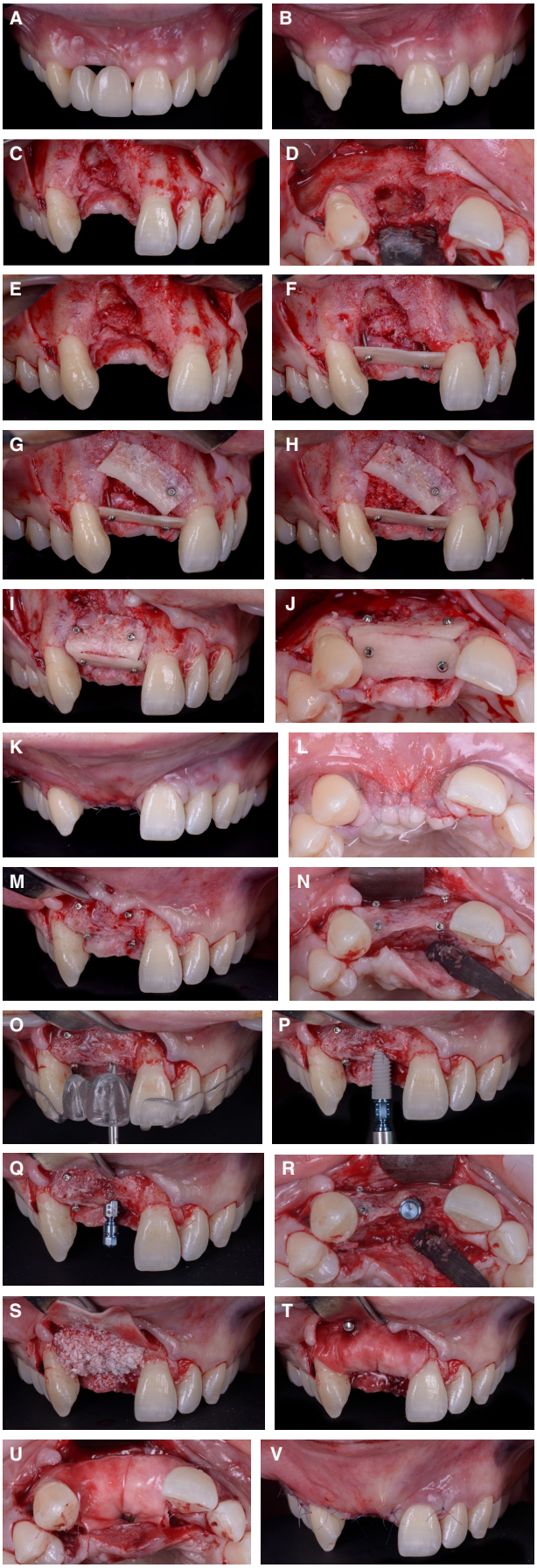

FIGURE 3 Representative case of an anterior maxillary vertical defect treated with the bone shell technique. A, Labial preoperative view of the defect and its relationship with the prosthetic rehabilitation. B, Vestibular shifted flap design. C-E, Labial, occlusal, and lateral views of the bone defect. F-H, Stabilization of the occlusal and buccal bone shells and filling of the regenerative space with bone chips. Both the shells and bone chips were obtained from the extraoral splitting and scraping of an autogenous bone block harvested from the linea obliqua externa of the mandible. I, J, Labial and occlusal views of the bone reconstruction after the removal of sharp edges. K, L, Labial and occlusal views of the first intention wound closure. M, N, Labial and occlusal views of the reconstructed bone at surgical reentry, 4 mo after surgery. O-R, Labial and occlusal views of the prosthetically guided implant placement. S-U, Contour augmentation with demineralized bovine bone matrix and a collagen membrane after implant placement. V, First intention wound closure

content of cancellous bone.[84,93,94] Such a difference is based upon the capacity of endosteal osteoblasts and sprouting capillaries to form osteoid and new vessels directly on the surface of cancellous bone trabeculae, whereas revascularization and bone formation in the presence of cortical grafts occur following the path of the pre-existing Haversian system, through a process called creeping substitution. Such a process occurs at a much slower pace and can result in the persistence of islands of necrotic bone enclosed within the newly formed vital bone.[95,96] Donos et al[80] showed in a preclinical study that barrier membranes combined with a bone block, irrespective of their embryologic origin, exert a beneficial role in stabilizing initial bone gain after the reconstructive procedure when compared with bone block with no barrier membrane covering the grafts.

Based on those premises, further strategies have been developed aiming at promoting the revascularization of the grafted area:

1. The plates technique ("shell technique").[91] Thin bone laminae are utilized as space-making devices to delimit a regenerative space that is filled with particulated autogenous bone, in order to minimize the cortical component of the graft and thus facilitate the ingrowth of sprouting capillaries during healing.
2. The inlay bone block technique.[97] Here, a bone block graft is interposed within a segmental osteotomy of the vertically atrophic bone crest in order to sustain the displacement of the segmented bone in a coronal direction, without detaching the supracrestal soft tissues and related vascular network from the occlusal aspect of the mobilized fragment.

2.2.2 | Technical note

Similar to guided bone regeneration, vertical ridge augmentation through a bone block is a complex, technique-sensitive intervention where optimal soft and hard tissue management is indispensable to avoid short- and long-term complications.[66] In this context, the management of the soft tissues follows the same principles and technical

TABLE 3 Studies reporting on the effectiveness and long-term stability of vertical ridge augmentation by means of bone block

Authors (y)	Study design	Patients/sites	Number of implants, baseline (final)	Follow-up of implants, mean (range) (mo)	Surgical technique	Graft origin	Location	Vertical bone gain at site level, mean ± SD (mm)	Complication rate	Marginal bone loss (mm)
De Stavola and Tunkel (2013)[101]	Case series (prospective)	10 10/10 10	18 (18)	12	Autologous bone using the shell technique (staged)	Autologous	Single or partial anterior or posterior maxilla or mandible	6 ± 1.29	No exposure of the graft and no complications with the donor site (0%)	Not reported
Mangano et al (2014)[159]	Case series (prospective)	10 10/10 10	10 (10)	12	Custom-made hydroxyapatite (milling from a block) (staged)	Synthetic graft	Single anterior or posterior maxilla or mandible	3.7 ± 0.82	One graft was exposed 2 mo after the procedure and the most coronal portion of the graft had to be removed (10%)	Not reported
Nissan et al (2011)[160]	Case series (prospective)	20 20/not reported	31 (30)	42 (12-65)	Freeze-dried cancellous allograft (staged)	Allograft	Single or partial anterior maxilla	2 ± 0.5	Not reported	Not reported
Nissan et al (2011)[21]	Case series (prospective)	34 31/not reported	63 (62)	34 (6-59)	Freeze-dried cancellous allograft (staged)	Allograft	Single or partial anterior maxilla	2 ± 0.5	Not reported	Not reported
Peleg et al (2010)[122]	Case series (prospective)	13 13/16 16	26 (26)	26	Allogenic cortico-cancellous iliac graft (staged)	Allograft	Single or partial anterior or posterior maxilla or mandible	2.4 ± 1.09	No cases with exposure of the graft material (0%)	Not reported
Roccuzzo et al (2004)[123]	Case series (prospective)	18 18/18 18	37 (37)	Only reentry	Autologous block from ramus/symphysis ± titanium mesh (staged)	Autologous	Single or partial anterior or posterior maxilla or mandible	4.8 ± 1	Temporary paresthesia observed in five cases (27.8%). Exposure of the titanium mesh in four patients (22.2%)	Not reported

(Continues)

TABLE 3 (Continued)

Authors (y)	Study design	Patients/sites	Number of implants, baseline (final)	Follow-up of implants, mean (range) (mo)	Surgical technique	Graft origin	Location	Vertical bone gain at site level, mean ± SD (mm)	Complication rate	Marginal bone loss (mm)
Yu et al (2016)[137]	Case series (prospective)	21 21/21 21	21 (21)	73 (48-96)	Autologous bone using the shell technique (staged)	Autologous	Single or partial anterior maxilla	5.12 ± 1.05	Six patients required additional grafting (28.6%). One patient presented a membrane exposure (4.76%)	6 y: 0.77 ± 0.5
Jensen et al (2006)[97]	Case series (retrospective)	10 10/10 10	15 (15)	60	Interpositional graft using a cortical wedge obtained from the ramus (staged)	Autologous	Partial anterior maxilla	4.2 ± 0.92	Not reported	Not reported
Roccuzzo et al (2007)[16]	Controlled clinical trial	23 23/24 24	Not reported	Only reentry	Autologous from ramus/ symphysis ± titanium mesh (staged)	Autologous (test and control)	Single or partial anterior or posterior maxilla or mandible	Test: 4.8±1.5 Control: 3.6±1.4	Test: Four patients presented mesh exposure (33.3%) Control: One graft mobilization at implant placement (8.3%). Three incomplete integration of the graft (25%). One temporary paresthesia (8.3%). Two significant graft resorption (16.7%)	Not reported
Tunkel et al (2021)[124]	Case series (retrospective)	5 5/10 10	Not reported	12	Autologous/ allogenic bone plates using the shell technique (staged)	Autologous (control) Allograft (test)	Single or partial posterior mandible or maxillae	Test: 3.2 ± 0.3 Control: 3.9 ± 1.3	Temporary sensitivity disturbance on the donor side (20%)	Test: 0.2 ± 0.4 Control: 0.0 ± 0.2

TABLE 3 (Continued)

Authors (y)	Study design	Patients/sites	Number of implants, baseline (final)	Follow-up of implants, mean (range) (mo)	Surgical technique	Graft origin	Location	Vertical bone gain at site level, mean ± SD (mm)	Complication rate	Marginal bone loss (mm)
Chaushu et al (2021)[126]	Case series (retrospective)	16 16/16 16	73 (69)	48 (12-92)	Allogenic bone block (staged)	Allograft	Anterior mandible in edentulous	10.7 ± 3.2	Sensory/motor impairment (5.5%) Early implant failure (5.5%) Late implant failure (2.2%)	Not reported
Pfaffeneder-Mantai et al (2022)[127]	Case report	1 1/2 2	6 (6)	19	Custom-made allograft block (staged)	Allograft	Maxillary full-arch	Not reported	No complications	Not reported
Khoury and Hanser (2022)[103]	Case series (retrospective)	117 88/128 97	287 (223)	120 (120-204)	Autologous bone using the shell technique (staged)	Autologous	Single or partial posterior mandible	7.4 ± 2.6 (reentry) 6.7 ± 2.6 (10 y)	Delayed wound healing (1.6%) Late bone exposure (1.6%) Infection (0.8%) Gingival recession on neighboring teeth (2.3%) Early screw exposure (24.2%) Implants lost (1.7%)	1 y: 0.66 ± 0.38 3 y: 0.69 ± 0.32 5 y: 0.72 ± 0.31 10 y: 0.75 ± 0.43
Nilius et al (2022)[125]	Case report	30 not reported/75 not reported	Not reported	36 (6-36)	Custom-made allograft block/shell technique with allograft plate (staged)	Allograft	Maxillary full-arch	5.73 ± 3.5	Block/plate exposure (not reported)	*Blocks* 1 y: 1.03 ± 1.54 2 y: 2.14 ± 2.20 3 y: 3.83 ± 1.98 *Shell technique* 1 y: 1.71 ± 1.6 2 y: 2.42 ± 2.83 3 y: 5.51 ± 3.8
Schlee and Rothamel (2013)[119]	Case series	3 3/3 3	9 (9)	12	Custom-made allograft block	Allograft	Posterior mandible	Not reported	Partial exposure of a block (33.3%)	6 mo: 1.69 ± 3.31 12 mo: 1.64 ± 1.22
Blume et al (2019)[133]	Case report	1 1/2 2	4 (4)	10	Custom-made allograft block	Allograft	Premolar area in the maxilla	3.5 ± 1.1	None (0%)	Not reported

Abbreviations: BOP, bleeding on probing; C, control; CBG, clinical bone gain; CCT, controlled clinica trial; COM, complication; IS, implant survival; ISUC, implant success; NC, no control; NR, not reported; PPD, peri-implant probing depth; PRGF, platelet rich growth factors; prosp, prospective; ret, retrospective; T, test.

TABLE 4 Studies reporting on the effectiveness and long-term stability of vertical ridge augmentation by means of distraction osteogenesis

Authors (y)	Study design	Patients/sites	Follow-up after functional loading (mo)	Surgical technique	Location	Vertical bone gain at site level mean ± SD (range) (mm) Mean bone gain/ Mean bone defect (%)	Healing complications	Marginal bone loss (mm)
Chiapasco et al (2004)[152]	Case series (prospective)	37/37	12-42	Intra-oral distractor	Full or partial anterior or posterior maxilla or mandible	9.9 (4-15) Not reported	21.6%	1.4 ± 0.4
Chiapasco et al (2004)[81]	Randomized controlled trial (parallel)	Control: 10/10	12-36	Test: Expanded polytetrafluoroethylene titanium-reinforced membrane + autologous (1: simultaneous; 2: staged) Control: Intra-oral distractor	Maxilla and mandible	Control: Not reported	Lingual inclination bone fragment Control: 20%/20%	*Baseline* Control: 0.50 ± 0.4 *1 y* Control: 1.13 ± 0.3 *3 y* Control: 1.41 ± 0.3
Jensen et al (2002)[143]	Case series (prospective)	28/30	60	Transcortical distractor	Partial anterior maxilla	6.5 ± 1.4 (3-15) 100	Relapse of the segment: 50%/46.6% (mean: 1.6 ± 1.5 mm) Device failure: 17.9%; 20%	1 ± 1.3
Froum et al (2008)[148]	Case series	30/30	34-60	Endo-osseous distractor and extraosseous distractor	Partial anterior or posterior maxilla or mandible	7.8 ± 4.9 (3.5-13)	Need for additional soft tissue surgery: 100%/100% Need for additional hard tissue surgery: 60%/60% Lingual inclination bone fragment: 73.3%/73.3% Failure to achieve buccal augmentation: 73.3%/73.3% Diminished vestibule (extraosseus distractors only): 43.3%/43.3% Flap dehiscence (extraosseus distractors only): 13.3%/13.3% Compromised esthetic result: 40%/40% Temporization difficulties: 10%/10% Distractor instability: 6.6%/6.6% Infection: 6.6%/6.6% Resorption of the transport segment (intraosseus distraction only): 3.3%/3.3% (full), 26.6%/26.6% (partial)	Not reported
Klug et al (2001)[153]	Case series	10/13	2-19	Distractor and titanium membrane in 4/13 sites	Mandible	7.5 ± 1.27 (6-9) Not reported	Dehiscence: 20%/15.4% Device failure: 10%/7.7%	Not reported
McAllister (2001)[154]	Case series (prospective)	7/10	12-30	Endosseous distractor	Maxilla and mandible	7 (5-9) Not reported	Slight setting: 14.3%/10% Incomplete bone consolidation: 28.6%/20%	Not reported

TABLE 4 (Continued)

Authors (y)	Study design	Patients/sites	Follow-up after functional loading (mo)	Surgical technique	Location	Vertical bone gain at site level mean ± SD (range) (mm) Mean bone gain/ Mean bone defect (%)	Healing complications	Marginal bone loss (mm)
Rachmiel et al (2001)[149]	Case series	14/14	6-20	Endosseous distractor	Maxilla and mandible	10.3 ± 1.3 (8-13) Not reported	Device failure: 7.1%/7.1% Neurological alterations: 7.1%/7.1%	Not reported
Raghoebar et al (2002)[150]	Case series	10/10	6-20	Distractor	Mandible	6.8 ± 0.8 (6-8) 96.1 ± 8.7	Dehiscence: 10%/10%	Not reported
Kunkel et al (2005)[155]	Case series	10/10	48	Intraosseous implant–shaped distractor	Mandible	7.3 ± 1.6 Not reported	Infection: 20%/20% Loosening of the distractor: 10%/10%	Not reported
Iizuka et al (2005)[156]	Case series	7/7	12	Bidirectional distractor	Anterior mandible and maxilla	11.9 ± 2.6 (10-15) Not reported	Insufficient anterior inclination: 28.6%/28.7%	Not reported
Enislidis et al (2005)[157]	Case series (retrospective)	37/45	36	Intraosseous distractor: (14) Subperiosteal distractor: (31)	Mandible	8.2 (5-15) Not reported	*Major complications* Fracture of basal bone or transport segment: Not reported/8.9% Device failure: Not reported/2.2% Mechanical problems: Not reported/6.7% *Minor complications* Dehiscence: Not reported/26.7% Infection: Not reported/4.4% Tilting of segment or wrong direction: Not reported/13.3% Neurological alterations: Not reported/4.4% Pain: Not reported/11.1% Swelling: Not reported/8.9%	Not reported
Türker et al (2007)[151]	Case series	10/10	12	Intraosseous distractor	Mandible	9.6 ± 1.8 (6-12) Not reported	Resorption of the segment: 10%/10% Lingual inclination bone fragment: 10%/10%	Not reported
Schleier et al (2007)[158]	Cohort (retrospective)	21/21	30	Unidirectional: (10) Bidirectional: (11)	Maxilla and mandible	Unidirectional: 5.3 ± 1.8 Not reported Bidirectional: 6.1 ± 2.3 Not reported	Crestal bone dislocation and infection Unidirectional: 60%/60% Bidirectional: 27.3%/27.3%	Not reported
Chiapasco et al (2007)[15]	Randomized controlled trial	Control: 9/9	42	Test: Autologous block graft Control: Intra-oral extraosseous distractor	Mandible	Control: 5.3 ± 1.6 (2-8) Not reported	Lingual inclination bone fragment: 22.2%/22.2% Incomplete distraction: 11.1%/11.1%	*Baseline* Control: 0.2 ± 0.3 *1 y* Control: 0.9 ± 0.4 *3 y* Control: 1.0 ± 0.4

Abbreviations: C, control; CCT, controlled clinica trial; NC, no control; NR, not reported; prosp, prospective; ret, retrospective; T, test.

steps described for guided bone regeneration, which include the elevation of a full-thickness mucoperiosteal flap, its passivation through periosteal fenestration/periosteoplasty, and the closure over the regenerated site with a multilayer suturing approach, to achieve a watertight first intention wound healing.

Soft tissue management

In order to facilitate the achievement of primary closure, multiple technical approaches implying soft tissue management and suturing techniques have been described: (a) the free curtain flap and papilla shift technique for anterior regions;[39] (b) the zone-specific lingual flap advancement technique;[98] (c) the vestibular shifted flap design;[99] (d) the suspended external-internal suture;[100] and (e) the tunnel approach.[101–103] See "Technical note" for a description of these techniques.

Hard tissue management

With regard to hard tissue management, the following steps have been recommended based on the adopted technique:

1. After flap elevation, the bone defect is thoroughly degranulated to remove any soft tissues remnants, and decortication holes are then made with a round bur to promote angiogenesis.
2. Bone block harvested from the mandibular ramus,[104] chin,[105] iliac crest,[106] or parietal calvarium[107] are modeled to obtain adaptation to the recipient site and then rigidly fixed with titanium mini-screws (1.5-2 mm diameter).
3. Sharp edges from the bone block are carefully removed with a diamond bur or piezoelectric insert, in order to avoid any risk of flap perforation.
4. Remaining gaps between the bone block and recipient site are filled with autogenous bone chips collected during the harvest of the bone block.
5. A layer of slowly resorbable bovine bone matrix mixed with autogenous bone chips can be placed over the grafts and stabilized with collagen membranes, in order to reduce the risk of bone resorption.[108,109]
6. After the completion of the reconstructive phase, periosteal releasing is performed and first intention closure is achieved.
7. Surgical reentry is performed between 4 and 12 months after surgery, to allow the placement of dental implants.[104]

Shell technique

See Figure 3 for a representative case of the shell technique.

1. After flap elevation, the bone defect is thoroughly degranulated to remove any soft tissues remnants.
2. The bone block harvested from the mandibular ramus is split in two parts and then scraped in order to create two 1 mm thin bone shells.[110,111]
3. Based on the defect configuration, the two bone shells can be fixed at the buccal and occlusal aspect of the defect, or at the buccal and lingual one. Fixation is performed with titanium microscrews (1-1.2 mm diameter).
4. Particulated autogenous bone collected from scraping the split bone block is placed within the regenerative space delimited by the two shells.
5. Sharp edges from the shells are carefully removed with a diamond bur or piezoelectric insert, in order to avoid any risk of flap perforation.
6. After the completion of the reconstructive phase, periosteal releasing is performed and first intention closure is achieved.
7. Surgical reentry is performed 4 months after surgery, to allow the placement of dental implants.[91] At this time point, horizontal relining of the vertically augmented bone can be performed with a layer of slowly resorbable bovine bone matrix stabilized by a resorbable collagen membrane, in order to reduce the risk of bone resorption over time.[92]

2.2.3 | Inlay bone block

1. A modified flap design is adopted, to preserve the periosteal attachment and related vascularization on the occlusal aspect of the vertically atrophic crest. Thus, a para-crestal horizontal full-thickness incision is performed in the alveolar mucosa to expose the alveolar process apical to the defect.
2. A segmental osteotomy is performed with a horizontal apical cut and a mesial and distal vertical cut to separate the coronal portion of the bone crest presenting the defect from the basal bone.[97]
3. The osteotomized segment is then elevated coronally.
4. The bone block is shaped and inserted within the horizontal osteotomy, in order to support the coronal advancement of the osteotomized segment. This can be stabilized with either osteosynthesis plates[97] or by simple mechanical friction with the additional protection of a collagen membrane.[112]
5. After completion of the reconstructive phase, periosteal releasing is performed and first intention closure is achieved.
6. Surgical reentry is performed 2 months[112] to 4 months later[113] to allow the placement of dental implants.

2.2.4 | Indications and limitations

Autogenous bone block grafts have been extensively used for vertical ridge augmentation for more than 35 years, with their main advantage (compared with the use of particulate bone grafts) of being easily fixed with osteosynthesis screws.[114] Several donor sites have been investigated, including extraoral sources, such as the iliac crest,[115] or intra-oral sources, such as the symphysis or the ramus.[116] Among the different techniques used to increase the vertical ridge dimension with the aid of autogenous bone block, the so-called shell technique, using a thin cortical bone block to restore the contours of the alveolar ridge, is nowadays the standard-of-care technique,

as long as it reduces bone resorption to below 10%.[101] These low resorption rates could be reduced even further by combining the implant placement after ridge augmentation with relining with a particulated xenograft and a resorbable membrane.[92]

The following indications can be advocated for bone block grafting:

1. Simultaneous grafting and implant placement.[117]
2. Extensive vertical defects in partially or totally edentulous patients, especially in the mandible.

In contrast, limitations for autogenous bone block grafting are as follows:

1. Limited amount of intra-orally available bone.
2. Higher morbidity than with the use of particulated bone substitutes.

Somehow, these limitations could be overcome with the use an allogeneic bone block, which could be milled to suit the defect geometry following preoperative diagnosis with cone beam computed tomography in order to lessen the morbidity of the procedure.[118,119]

2.2.5 | Effectiveness based on clinical studies

The effectiveness of vertical ridge augmentation with bone block grafts has been evaluated in several investigations (Table 3).[16,21,97,101,103,120–127] Depending on the nature of the graft, the results provided have been heterogeneous, with the vertical bone gain ranging from 4.12 mm (95% confidence interval 3.11-5.13 mm) for autogenous bone block to 2.03 mm (95% confidence interval 1.88-2.18 mm) for allograft bone block according to a recent systematic review.[66] Also, when using autogenous bone, the choice of the technique seems to influence the results heavily, with worse results for onlay bone block (3.5 mm, 95% confidence interval 2.2-4.9 mm) than for the three-dimensional "shell technique" (2.0 mm, 95% confidence interval 1.9-2.2 mm). Anyway, it must be acknowledged that the amount of vertical ridge augmentation obtained always depends on the baseline dimension of the defect, so these numbers should be interpreted with care (Table 3).

More recent data seem to support better results for the shell technique versus classical onlays for vertical ridge augmentation. Specifically, a recently published retrospective study by Khoury and Hanser[103] reported the results of 117 consecutively treated patients with 128 grafted sites followed for up to 17 years, with 88 patients and 97 augmented sites followed up for at least 10 years. In this study, the mean vertical bone gain was 7.4 ± 2.6 mm at the reentry, whereas the results after 10 years of follow-up remain pretty stable, accounting for a mean vertical ridge augmentation of 6.7 ± 2.6 mm.[103] However, the limited amount of intra-orally available bone has led to an increasingly important role for both allogeneic and xenogeneic graft materials.[128–130] Thus, the use of allogeneic cortical bone plates to be used in the shell technique has also become a reality, solving the problem of insufficient intra-oral bone quantity and reducing the morbidity of these procedures. Furthermore, a recent publication comparing both horizontal and vertical ridge augmentation with allogeneic and autogenous bone plates using the shell technique did not find any difference among them, at least as long as augmentative relining at implant placement with a xenogeneic bone substitute and a collagen membrane are used in order to reduce the resorption processes.[124]

The feasibility and security of allogeneic bone block manually milled before surgery has been confirmed in several clinical studies.[131,132] The main advantages of this technique are the time reduction and ease of graft adaptation. For example, Chaushu et al[126] recently published a retrospective case series showing impressive clinical results after the use of an allograft bone block (vertical bone gain approximately 10 ± 3 mm); however, it should be acknowledged that all the cases included in the study were edentulous subjects in the mandible in which vertical ridge augmentation was performed in the anterior region, which may be a completely different scenario to the posterior mandible in terms of healing pattern.

Also, allogeneic bone blocks specially designed and manufactured using computer-aided design/computer-aided manufacturing have been used for horizontal and vertical ridge augmentation, thus allowing the preshaping of bone block grafts and to plan the position of the fixation screws. One of the first reports was published by Schlee and Rothamel,[119] who showed that this strategy was efficient in terms of new bone formation with reduced patient morbidity, decreased surgery time, and high patient acceptance. Another case report, by Blume et al,[133] demonstrated the regeneration of two large osseous defects with customized computer-aided design/computer-aided manufacturing allogeneic bone blocks that perfectly matched the defect geometry and enabled implant placement according to the initial treatment plan. However, even if both bone blocks were covered by a porcine pericardium membrane, the rate of resorption of both was heterogeneous. Finally, a retrospective case series with 30 patients (15 of them treated by allogeneic bone block) showed a 5.73 ± 3.5 mm vertical bone gain in maxillary full-arch restorations following an "advanced backward planning" procedure (ie, based on a digital prosthetic mock-up, the correct implant positions and the bone block size needed to overcome the bone loss were anticipated).

2.2.6 | Postoperative complications

Since vertical ridge augmentation procedures are technically demanding, it is compulsory to assess the rate of complications to properly evaluate their effectiveness, as it is insufficient just to consider the vertical gain obtained. The most common complication in vertical ridge augmentation procedures with a bone block is the exposure of the graft, with or without infection. A recent systematic review prepared for the XV European Workshop in Periodontology

reported an overall risk for vertical ridge augmentation procedures of 16.9% (95% confidence interval 12.5%-21.2%), whereas it was 23.9% with the use of a bone block (95% confidence interval 11.3%-36.6%).[66] In the particular case of a bone block, apart from wound dehiscence/graft exposure, other complications may arise as a consequence of the need for a second surgical site (donor site) in the case of autogenous grafts; namely, temporary paresthesia, pulp necrosis of lower incisors, and so on. Furthermore, incomplete integration of the bone block may lead to its mobilization at the time of implant placement.[134]

Even though no randomized controlled trials are available comparing the incidence of complications between autogenous or allogeneic bone blocks, it seems that bone block allografts are more technique sensitive, and so clinical training is strongly recommended for clinicians unfamiliar with the use of this type of bone graft. Complications include opening of the incision line (possibly due to inadequate suturing technique), perforations of the mucosa, and infections leading to partial or total bone block loss being more common than for autogenous bone block.[135] For example, the previously mentioned publication by Khoury and Hanser[103] reported that for 117 patients (128 sites) there were just 1.6% cases of bone exposure (although 24.2% of early screw exposure), 0.8% infections, and just four implants lost (1.74%) over a 10-year period; and data from another retrospective case series including 101 consecutive patients (137 sites) treated with cancellous bone block allografts showed a 30.7% incidence of membrane exposure, a 13% incidence of infected bone block, and an implant failure rate of 4.4% with a follow-up that ended at the time of placement of the implant-supported restorations.[136]

2.2.7 | Long-term predictability

Long-term results of vertical ridge augmentation procedures performed by means of bone blocks are seldomly reported, and the same could be said for the incidence of biological complications (ie, peri-implant mucositis and peri-implantitis) on the implants placed in the augmented bone. However, if the radiographic marginal bone levels are evaluated once the implants are restored in a series of studies on vertical ridge augmentation by means of bone block grafting (Table 3), it can be observed that marginal bone loss is below 1 mm in periods up to 10 years when autogenous bone following the "shell technique" have been used.[101,103,124,137] In contrast, marginal bone loss reported in studies using "conventional" bone blocks (specifically those of allogeneic origin) is significantly higher, ranging between 1 mm at 1-year follow-up and up to 3 mm at 3 years after implant placement.[119,125] This may be related to the poor revascularization leading to increased resorption of the grafted area, which may be related more to the different methods for shaping and processing bone block grafts than with their origin. Nevertheless, the allogeneic/xenogeneic three-dimensional printed bone block require long-term results from comparative studies to determine the predictability of their outcomes.

2.3 | Distraction osteogenesis

2.3.1 | Biological foundation

Distraction osteogenesis is an advanced hard and soft tissue engineering protocol for the treatment of anatomical deformities. It was originally applied on long bones in orthopedic surgery[138,139] and then later found extensive application on membranous bones, in the correction of cranio-maxillofacial malformations,[140] in orthognathic surgery,[141] and in the correction of severe atrophies of the alveolar processes to allow the placement of dental implants.[15,142,143]

Its biological rationale is based on the segmentation of the atrophic bone and on the progressive displacement of the bone segment and the attached soft tissues in a coronal direction to create a secluded regenerative chamber where new bone and soft tissues are formed throughout the distraction process.[138] Such displacement is achieved through a segmental osteotomy that separates the atrophic crest from its basal bone; the subsequent application of a distraction device then progressively opens the osteotomy line with slow and calibrated tension forces.[15,138,144]

Evidence from preclinical studies, showed that the regeneration chamber progressively undergoes an intramembranous ossification process in a centripetal direction.[145–147] During the first days after surgery, the regeneration chamber is initially filled with a blood clot and fibrous tissue; then, after 10 days of distraction, a fibrous matrix is present, with fibers oriented in the direction of elongation. New bone formation starts at the periphery of the regeneration chamber with the formation of slender calcified spicules, oriented in the direction of distraction, that become covered by osteoblasts. At 2 weeks, osteoclastic activity is present behind the extending front of bone formation and the slender spiculae undergo a structural remodeling, becoming thicker trabeculae separated by wider spaces. At 4 weeks, the bone trabeculae have progressively extended to the central zone of the regeneration chamber, re-establishing bone continuity. At 12 weeks, the completion of distraction, the regeneration chamber is completely filled by new bone.[145–147]

2.3.2 | Technical note

Regardless of the site of application, the following basic principles have been described:[138]

1. Osteotomy of the bone site with minimal periosteal stripping.
2. Latency period of 3, 5, or 7 days, depending on the surgical site.
3. Distraction rate of 1.0 mm per day (0.5-2.0 mm).
4. Distraction through continuous force application is best, albeit a device activation twice a day is more practical and allows for better patient compliance.
5. Consolidation should be extended until a cortical outline can be seen radiographically across the distraction gap, which usually requires 6 weeks.

Currently, the majority of those principles is still applied for distraction osteogenesis of the atrophic edentulous ridges.[15,142,148] Specifically, the following steps are followed:

1. A modified flap design, similar to the one described for inlay bone blocks, is adopted that preserves the supracrestal soft tissue attachment and related vascularization on the occlusal aspect of the vertically atrophic crest. Thus, a para-crestal horizontal full-thickness incision is performed on the alveolar mucosa to expose the alveolar process apical to the defect.
2. A segmental osteotomy is performed with a horizontal apical cut, combined with a mesial and distal vertical osteotomy, to separate the coronal portion of the bone crest presenting the defect from the basal bone.
3. The intra-oral distractor is fixated to the basal bone and the osteotomized bone segment with titanium mini-screws.
4. Once fixated, the distractor is immediately activated to check the vector of distraction and the undisturbed mobility of the bone segment.
5. The segment is repositioned at its initial position and the surgical access is sutured by first intention, leaving access exclusively to the most coronal part of the distractor to allow its progressive activation from the patient.
6. Seven days after surgery, distraction is started with either a fixed rate (eg, 0.5 mm every 12 h since the first day of distraction)[15] or an increasing rate over time (eg, 0.4 to 0.6 mm/day for the first 3 days, followed by 1.2 mm a day for the following days[148]).
7. Distraction osteogenesis is carried out until the desired bone augmentation is achieved.
8. The distractor is maintained in place for 2-3 months after completing the distraction osteogenesis phase to allow bone maturation in the distracted segment (consolidation phase).
9. Surgical reentry is performed to remove the distractor device and place the dental implants in the augmented bone.

2.3.3 | Indications and limitations

The following indications are advocated for distraction osteogenesis:

1. Distraction osteogenesis is indicated prior to the implant placement in the case of severe vertical discrepancies in order to regenerate the bone.
2. Whenever it is desired to reduce the intermaxillary distance for better esthetics and function.
3. In scenarios where it is desired to augment the hard and the soft tissues simultaneously.
4. In highly damaged soft tissues where flap advancement is not feasible.

The following limitations are disclosed for distraction osteogenesis:

1. When the residual bone volume required for the fixation of the distractor and also the transported bone fragment dimensions are insufficient, it should be taken into account that a residual vertical bone height of at least 6-8 mm is usually required and that small transported fragments (eg, single-tooth defect) may potentially lead to more complications due to vascular impairment.[81,143,149–151]
2. Whenever it is desired to augment the ridge in both the vertical and horizontal directions.
3. Posterior ridges are often more complicated due to access and the morphology of the ridges.

2.3.4 | Effectiveness for vertical ridge augmentation based on clinical studies

The effectiveness of distraction osteogenesis has been evaluated in different case series (Table 4),[143,148–158] and it was demonstrated that this surgical technique is able to vertically regenerate a considerable amount of bone, ranging between 5 and 12 mm depending on the original extent of the defect. Chiapasco et al,[15] in a randomized controlled trial study design on nine patients, reported a mean vertical regeneration of 5.3 ± 1.6 mm using both intra-oral and extraoral distractors. In agreement with these results, a recent systematic review and meta-analysis calculated a mean vertical bone gain of 8.04 mm (95% confidence interval 5.68-10.41 mm).[66] Hence, the predictability of the results obtained with this approach is high even in cases of severe vertical discrepancies. Nonetheless, a high percentage of complications is associated with this procedure, and some of them may lead to the failure of the vertical regeneration, such as device failure/mechanical problems,[143,155,157] fracture of the basal bone/transport segment,[157] and bone resorption.[148,151] In comparison with other techniques, it is rather difficult to draw conclusions as the comparative studies available did not analyze the difference in terms of vertical bone gain.[15,81] Nonetheless, the mean vertical bone gain values reported in studies adopting distraction osteogenesis are higher than with other techniques (eg, guided bone regeneration, bone block).[36,66]

2.3.5 | Long-term predictability

Data on the stability of the marginal bone loss around implants in regenerated bone after distraction osteogenesis are scarce in literature. In fact, most studies did not report information regarding the implant stability of the peri-implant bone over time. A 5-year prospective case series on 48 implants showed a marginal bone loss of 1 ± 1.3 mm,[143] and another longitudinal study from the same research group showed a marginal bone resorption of 1.4 ± 0.4 mm in a 1- to 3.5-year study on 138 implants.[152] Two randomized controlled trials showed that, during the first year, marginal bone remodeling was roughly 0.6-0.7 mm on average and that bone levels were quite stable up to 3 years.[15,81] In addition, based on these two latter

studies, the amount of bone resorption following autologous block graft and guided bone regeneration by means of polytetrafluoroethylene membranes before the implant placement was higher than with distraction osteogenesis[15,81] and the number of successful implants was higher in distraction osteogenesis than with guided bone regeneration.[81]

3 | CONCLUSION

Vertical ridge augmentation is feasible and effective to restore esthetics and function in atrophic ridges. Different therapeutic modalities have been advocated to achieve vertical bone gain. All these techniques require an orchestrated sequence of maneuvers, implying soft and hard tissue management to minimize the risk of complications. In particular, guided bone regeneration combined with bone block is a technically demanding surgical procedure in regard to soft tissue management and longer healing periods. On the other hand, distraction osteogenesis is faster, with less morbidity, and may not demand high skills for soft tissue management; nevertheless, its application is limited to scenarios that do not demand lateral ridge augmentation simultaneous to vertical ridge augmentation.

CONFLICT OF INTEREST

The authors have no direct financial interests with the products and instruments listed in the paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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