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REVIEW ARTICLE

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Bone reconstruction of extensive maxillomandibular defects in adults

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1 | INTRODUCTION AND HISTORICAL DEVELOPMENT

Extensive maxillomandibular defects have been integral to reconstructive oral and maxillofacial surgery for more than 100 years. Dentists often performed primary care during World War I for acute battlefield injuries. It became evident that modern warfare has increased facial injuries, including to the jaws.[1] Complex facial traumata were treated with dental techniques like splinting and occlusal fixation.[2] Apart from warfare, another driving force was the development of tumor surgery starting in the mid-19th century. Jaw resections became more common where there was no possibility of reconstruction. It was in 1850 when the French dentist Préterre tried to form an alloplastic reconstruction of a jaw defect using a prosthesis. This led to discussions about functional and esthetic outcomes.[3] A wide field of dental resection prostheses was developed in the second half of the 19th century, as described in a well-written narrative review by Sigron.[4] Modern obturators or alloplastic reconstruction can be seen as developments in this field. Ollier was the first to publish landmark biological aspects of grafting in 1891,[5] describing the differences between autologous, homologous, and heterologous grafts. With a focus on graft properties, it was postulated that only viable, autologous bone could be successfully transplanted and that the periosteum plays a crucial role in graft survival. Histological studies from Barth[227] from the same time showed that, after grafting, the periosteum and bone marrow become nonvital. Starting from the recipient bed, and depending on its vitality, new blood vessels revascularize the graft. Barth drew attention to the viability of the recipient bed and the vascularization. Modern ideas regarding the viability of the recipient site, the bony envelope, and graft vascularization with resorption and revitalization, are related to this work. After some case descriptions, in 1911 Lexer published the first systematic analysis of free bone grafting of mandibular defects,[6] when the recipient bed was categorized as "strong", "weak", and "incapable". This constitutes a systematic approach that is still used today to describe the indication for microvascular grafts to reconstruct "incapable" osseous deficiencies. Another significant contribution of his work was explaining the need for immobilization. Gerry used an acrylic stent and wires to shape and fixate the graft material.[7] Freeman described the first functional, stable bridging plate in its modern form in 1948.[8] These ideas of immobilization and primary bone healing led to the development of large compression plates for fracture healing at the mandible.[9] In the 1970s, mini plates and screws allowed safe fixation of osseous grafts using intra-oral approaches.[10,11] A comprehensive overview of bony maxillary and mandibular reconstructions followed in the first half of the 20th century, published by Hjørting-Hansen.[12] In 1950, Converse in the USA[13] and Clementschitsch in Austria[14] started to successfully transplant nonvascularized autologous grafts from the iliac crest onto the maxillofacial area. The availability of antibiotic prophylaxis led to further development in this field.[15] However general anesthesia is mainly needed for extensive bone reconstructions.

Many of those historical bone grafting principles are generally accepted. After considering the indications for extensive craniomaxillofacial osseous reconstruction, the respective recipient site principles, local/systemic factors of influence, techniques for stabilizing the grafts, and using different bone grafts must be considered. Also, other alternatives to "biological" augmentations, such as alloplastic materials, need to be discussed.

2 | INDICATIONS

A clear definition of "small" and "large" craniomaxillofacial bone defects is missing in the literature. A systematic review stated that a mean horizontal and vertical bone gain of 3.7mm is possible using particulated materials. Bone blocks or other techniques are needed for more significant deficits.[16] Others state that a vertical augmentation above a threshold of 2.55mm poses a substantial risk for complications.[17] Even so, the type of reconstruction is also based on other properties, such as location, local and systemic factors, as well as patients' characteristics.[17–20]

2.1 | Alveolar reconstruction

Alveolar bone reconstruction of the maxilla and/or the mandible following atrophy was a significant challenge before dental implants were available. A landmark work from Tallgren in 1975 demonstrated the effect of denture wearing on the long-term atrophy of the mandible.[21] Recently, it was shown that using two implants for fixation of dental protheses can slow down bone resorption in the edentulous jaws.[22] Despite shorter and narrower implants, especially in the esthetic zone, a predictable bony and soft tissue reconstruction remains the clinical and scientific focus.[23–25] In conclusion, a sizeable alveolar reconstruction that relies on parameters such as local and systemic factors, the surgical incision and grafting technique, and the grafting material, is still needed in many cases.

2.2 | Continuity defects of the mandible

For reconstruction of continuity defects of the mandible, free iliac crest grafts were the historical standard, requiring an extraoral approach without a predictable option for primary reconstruction.[26–28] A staged approach with resection, then later a nonvascular iliac crest graft for reconstruction, followed by the insertion of dental implants, led to predictable results.[29] Nowadays, these defects, with poor regenerative capacity of the recipient bed, difficult immobilization, and low vascularization properties, have become a domain of microvascular anastomosed grafts. Those transplants allow the primary reconstruction of soft and hard tissues and avoid resorption. Besides, the principle of rigid fixation using bicortical screws and ridged bridging plates applies.[30]

2.3 | Midface/orbital reconstruction

Midfacial reconstruction is often indicated following trauma or tumor resections.[31,32] Also, syndromes may lead to malformations of the zygoma and midface.[33] The main issue in such cases is to allow a precise, unique reconstruction in the planned position. This is done using various autologous grafts,[34] but alloplastic grafts can be used if sufficient soft tissue coverage is available. In conclusion, reconstruction of the midface and/or the orbit—which is not the focus of the present review—is challenging, and is primarily based on individual requirements.

3 | RECIPIENT SITE PRINCIPLES

3.1 | Local and systemic factors

The vitality of the bone bed is critical for graft healing. Local factors like the cleft area, knife-edged cortical ridges in the mandible, or anatomic variations, can be challenging. Also, a history of inflammatory diseases such as periodontitis might increase the risk of complications.[35] Whereas some report that older age increases the complication rates,[35] also as a result of impaired angiogenesis,[36] others could not find a significant difference.[37] Nevertheless, medical conditions also have to be taken into account. Unfortunately, little is known about medically compromised patients and more extensive bone grafting. For example, sildenafil has been shown to impede early bone healing, but only in animals.[36] Other drugs, such as serotonin reuptake and proton pump inhibitors, have negatively influenced bone remodeling, although these data mainly refer to dental implant healing.[38–41] Earlier, in 1996, it was shown that osteoporosis might affect graft healing.[42] Vitamin D deficiency might also be a risk factor for graft complications.[43] However, substituting with vitamin D did not lead to a better histological outcome in sinus floor elevation.[44] Very few data on diabetes and more extensive augmentation procedures are documented. Animal data showed slower graft incorporation compared with a healthy control group.[45] Some authors have even commented that large block grafts should be avoided.[46] In brief, uncontrolled diabetes in particular has been recognized as a risk factor in craniofacial bone regeneration.[47] For smokers, less new bone formation and osteogenic marker expression was reported, leading to a higher complication rate after bone augmentation procedures.[35,48] After radiotherapy, bone grafts are known to be less predictable, and often, large grafts are also avoided.[49] In patients with low-dose bisphosphonate therapy (e.g., for osteoporosis treatment), the successful healing of autologous grafts is described in a case series.[50] Nevertheless, bisphosphonate treatment is related to negatively affecting osteogenesis, preventing osteointegration and the remodeling of bone grafts.[51] According to some authors, bone grafting should be avoided under high-dose antiresorptive therapy.[52] In conclusion, more evidence-based knowledge is needed on the impact of local and systemic risk factors regarding the reconstruction of significant maxillomandibular bone defects.

3.2 | Surgical incision designs for large grafts

The earliest standardized alveolar grafts were bone grafts in cleft lip and palate patients. Trauner described the typical buccal incision,[53] which became the standard.[54] The intention was to localize the incision far away from the graft so that minor dehiscence would not lead to direct contact with the graft. This technique, often called "poncho" incision, is still used in particular indications in maxillofacial surgery for large grafts (Figure 1).[55] The tunnel approach in the mandible was described in 1965, mainly for mechanical transplant fixation,[56] then came back in the 1980s to stabilize hydroxyapatite onlay grafts,[57] and is now used primarily for predictable beneficial wound-healing properties.[58] Originating from the marginal access in periodontal surgery with guided bone regeneration,[59,60] larger incision designs were developed using the crestal approach. Kleinheinz et al.[61] systematically analyzed the angiosomes of the oral cavity underlying the theoretical background for crestal incisions.[62] Buccal periosteal releasing incisions are needed to close the flap. A periosteal flap can allow a double-layer closure.[63] Urban et al.[64] illustrated the additional blunt lingual preparation a few years ago, allowing tension-free flap closure in the lateral mandible. In comparative studies, this coronally advanced lingual flap showed less dehiscence than other techniques (Figure 1A–C).[65]

3.3 | Onlay grafts

In cases of onlay grafts, the transplanted bone is placed on the recipient's bed. Onlay grafts to augment the atrophic mandible came to attention after the introduction of small osteosynthesis screws in the 1980s. Up until then, fixation was a significant issue, but one that was now finally solved. A widely discussed method in the atrophic mandible was the rib graft used by Davis et al.,[66,67] which was also described by others for the maxilla.[68] The authors also documented 80% graft resorption within the first 3 years. Accordingly, the iliac crest became the standard for large onlay grafts (Figure 2A,B), with long-term graft resorption data available in 1980.[69]

Currently, monocortical grafts from the inner table of the iliac crest are still used.[70] Interestingly, the harvesting morbidity was discussed relatively late.[71–73] Comparative (retrospective) data show a higher rate of donor site morbidity from the extraoral iliac crest and calvaria grafts compared with mandibular ramus grafts.[74] In the early 1990s, grafts were combined with immediate implants to overcome the resorption.[75–77] As graft healing was not always predictable,[78] later on, implants were inserted after the graft had been given time to heal.[79] However, graft resorption[80] and critical implant long-term survival[81] have both been the focus of research, even if many studies report stable implant success over 5 years.[73,82] Recently, long-term implant success in large iliac crest grafts has been discussed more critically.[72,83] Wiltfang et al.[84] covered the onlay grafts from the iliac crest with a thin layer of deproteinized bone matrix. Because this material does not show any resorption, it led to a significant reduction of graft resorption over a follow-up of 2 years.[85] An impressive long-term follow-up of 10 years after iliac crest grafting has recently been published with a promising rate of 95% implant survival.[86] Similar data have been presented for calvarial grafts, a technique only used by a few groups.[87,88]

3.4 | Inlay grafts

The transplanted bone is positioned interpositionally into the residual bone for inlay grafts. Historically, problems with graft fixation and healing led Härle to split the anterior mandible longitudinally, keeping the lingual soft tissue attached and reattaching the bone with wires. This "visor" or "sandwich" osteotomy technique increases the height of the mandible without the need for a graft (Figure 3).[89]

Other groups adopted this method.[90–92] It showed predictable outcomes with an implant survival rate of 94% after a mean follow-up of 3.7 years, but a high rate (41%) of (temporary) nerve disturbances.[93] One of the modifications still in use is the interposition graft.[94–96] The high rate of neurosensory disturbances (61% in one study) was also documented for the modifications of the interposition graft.[97] The method still has its place in the lateral mandible and anterior zone.[98,99]

In 1976, Farrell et al. published the first report of a Le Fort I osteotomy, with interposition of iliac crest bone (Figure 4A,B).[100] Other groups rapidly adopted this technique.[101] Long-term follow-up studies showed high implant survival rates over 10 years.[102] Early on, Sailer and Teuscher[103] pointed out that this technique also corrected the intermaxillary relationship; Sailer was the first to publish a report on single-stage Le Fort I osteotomy and implant insertion.[104] The immediate implant insertion led to more implant failures and was only adopted by a few clinicians.[105] The availability of piezosurgery and a better understanding of the anatomy has led to the combination

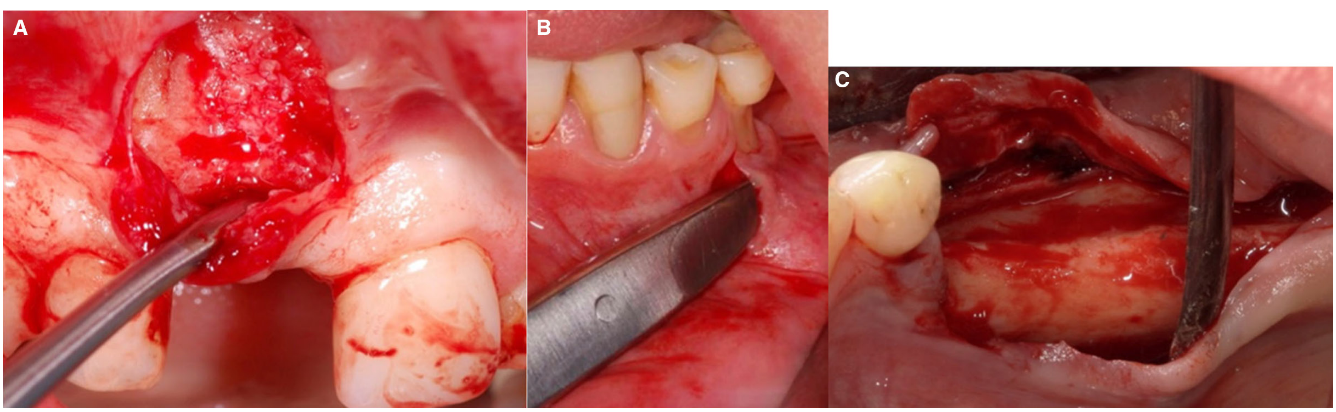

FIGURE 1 (A) "Nike" modification of the classical buccal "poncho" incision with thick, soft tissue for better vascularization; (B) Tunnel incision; and (C) Crestal incision with periosteal releasing incision and blunt lingual preparation.

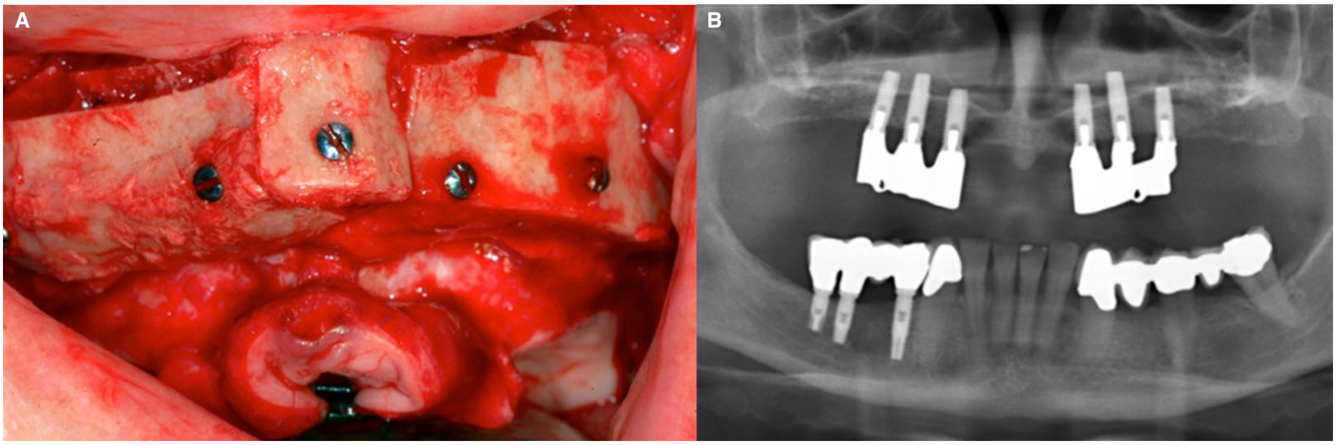

FIGURE 2 (A) Atrophic maxilla with iliac crest onlay graft and sinus floor elevation; and (B) The final result after dental restoration.

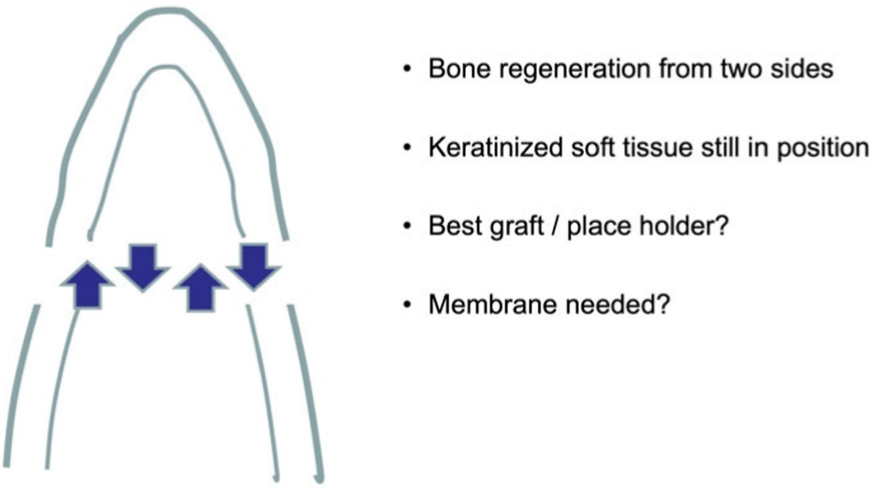

FIGURE 3 Interposition technique: the principle of the inlay/interposition graft with high regenerative potential.

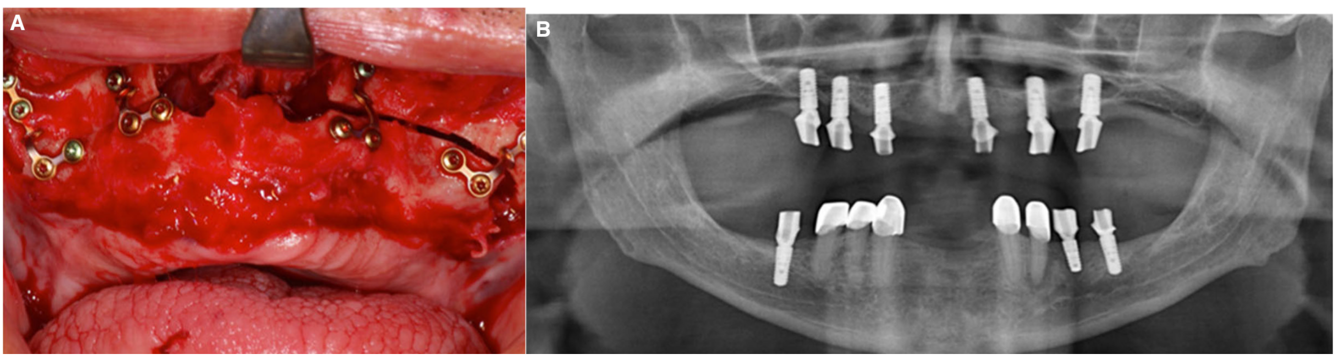

FIGURE 4 (A) Intraoperative situation of Le Fort I and sinus floor elevation; (B) With six implants inserted.

of sinus floor elevation and Le Fort I osteotomy.[106] Recently, a large cohort study with combined Le Fort I osteotomy and Sinus floor elevation was published after 5 years of follow-up, showing that sinus membrane perforation was relatively common. Also, fistula and wound dehiscence were noted. However, the long-term result regarding implant survival was promising.[107] In conclusion, onlay and inlay techniques are frequently used and must be considered appropriate for major bone augmentations individually.

4 | STABILIZATION OF PARTICULATED GRAFTS

In a broader sense, particulated graft materials can be subsumed as deriving from the patient (autologous), from other people (allogeneic), of animal origin (xenogenic), or artificially created (alloplastic), and each has a different regenerative potency.[16,108] In bone regeneration, graft materials, at least in their function as scaffolds, are essential for the attachment and differentiation of regenerative cells from the environment.[109,110] The graft materials mentioned are primarily used in guided bone regeneration. The principles of these techniques date back to experimental studies on the regenerative potential of periodontal tissues in the 1970s and 1980s. In theory, a separate space should be created by an occlusive barrier with the help of a membrane, which should only be recolonized by cells from the periodontal ligament or the alveolar bone while excluding other cells.[111] Much more important, however, seems to be the stability provided by the barrier membrane, which contributes significantly to the success of regeneration. It prevents soft tissue from collapsing into the defect and leads to the accumulation of growth factors.[60,112] Larger maxillomandibular defects might be regenerated using membranes with increased mechanical stability and space-maintaining capacity.

4.1 | Titanium meshes

Nonresorbable titanium meshes that rigidly maintain the osteogenic space – originating from classical osteosynthesis – may offer an attractive alternative to other major bone reconstruction techniques.[16,113,114] No differences in the outcome using collagen membranes versus titanium meshes were seen for more minor defects (<3–4 mm).[115–117] The disadvantages reported for titanium meshes are a long time for surgery and a need for additional manual skills because of intraoperative bending. The potential sharp edges and the problem in achieving tension-free suturing might result in soft tissue trauma and later exposure.[118–120] Modern techniques such as computer-aided design/computer-aided manufacturing aim to facilitate and increase precision in complex surgeries. Based on the patient's three-dimensional Digital Imaging and Communications in Medicine data, a virtual model of the jaw, including the defect, is generated. The necessary bone volume is added using reverse engineering software, and the titanium mesh is generated.[121] For improved surgeons' and patients' reported outcomes, prefabricated patient-specific meshes were introduced[120] and used with promising results, including less exposure (0%–33%) and shorter operation times (Figure 5).[55,114,122–124]

Nevertheless, a recent systematic review did not find a significant difference in exposure rates between conventional and customized meshes,[125] whereas another review did see this difference.[126] For (customized) titanium meshes, most reports analyzed horizontal augmentation of a maximum of 5–7 mm vertically and 4–5 mm in horizontal height, or did not give exact data on the augmented volume.[121,124,127–131] In one case series, a vertical and horizontal gain of up to 9 mm with an exposure rate of 1/10 cases was reported.[132] In "large" defects (mean reconstructed bone volume 1004 mm^3), Lizio et al.[228] summarized a failure rate of 5/19 sites. Chiapasco et al.[133] saw a mesh exposure in 11/53 locations, leading to a mean vertical and horizontal bone gain of 4.8 and 6.4 mm, respectively. Next to titanium, other materials such as polyetheretherketone,[129] polytetrafluoroethylene,[134] and hydroxyapatite/poly-lactide[135] were described.[130] Using polytetrafluoroethylene meshes, a mean vertical gain of 5.5 mm with no exposure rate (0/10) was seen.[134]

In conclusion, customized meshes are suitable for various bone defects, including complex and larger ones. A high exposure rate (Figure 6) and the need for secondary removal should be considered. In the case of such an adverse event, the site must be kept as clean as possible. Early mesh removal is not recommended if there are no signs of infection, because dental implant placement is often possible later on.[121]

Data on comparing meshes with other techniques in advanced defect situations are still needed. In addition, clinical data on nontitanium meshes have yet to be reported.

4.2 | Shell techniques

Another way to stabilize the particulate graft materials to reconstruct significant bone defects is the shell technique, which can be performed using autogenous or allogeneic cortical plates in different alveolar ridge defects.[136–141] In brief, a thin cortical block ("shell") is used to create a three-dimensional, secluded, stable space filled with autologous bone and/or a bone substitute material, enabling osseous regeneration (Figure 7).[138,142,143]

Also, three-dimensional printed templates and rigid resorbable barrier systems were reported as being applied as shells.[142,144–147] Like meshes, the shells are stable over the long term, and even complex defects can be reconstructed precisely using two or more bone shells.[148] The main complication constitutes dehiscences, which can be an even more frequent problem in extended augmentations[141]; in cases of autogenous shells taken from the ramus, a similar complication rate was reported.[149] Unfortunately, the shell technique is mostly reported for considerably more minor defects (<3–4 mm), and studies on more extensive reconstructions are scarce, even although these are biologically possible.[150–154] On the other hand, Khoury and Hanser reported a mean vertical gain using autogenous shells of 6.7 mm after a follow-up of 10 years.[58] Besides, shell techniques seem to achieve a more significant bone gain in combination with less resorption when compared with oral bone blocks.[154]

5 | AUTOLOGOUS DONOR SITES AND GRAFT PRINCIPLES

For decades, autogenous bone block grafting has been considered the therapeutic gold standard for small and medium-sized craniomaxillofacial defects. Together with the favorable properties of autogenous bone, they offer the advantage of good stability and resistance to deformation.[155] Autogenous bone blocks can be harvested from oral or extraoral sites, each with advantages and disadvantages.

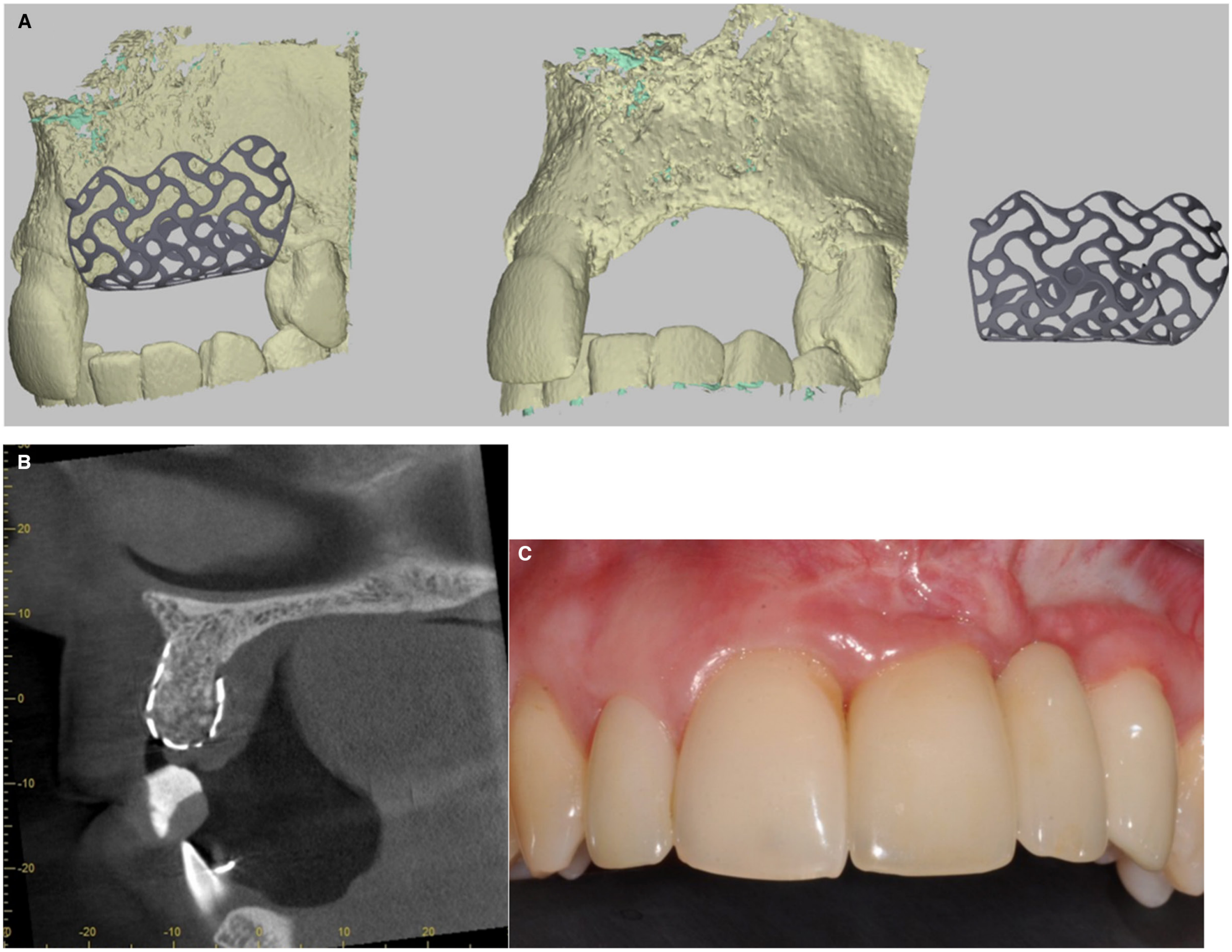

FIGURE 5 Mesh-based reconstruction of a mandible defect after resecting an odontogenic tumor. (A) Planning of a CAD/CAM titanium mesh; (B) CBCT after 6 months, before mesh removal and implant insertion; and (C) Final dental restoration. CAD/CAM, computer-aided design/computer-aided manufacturing; CBCT, cone beam computed tomography.

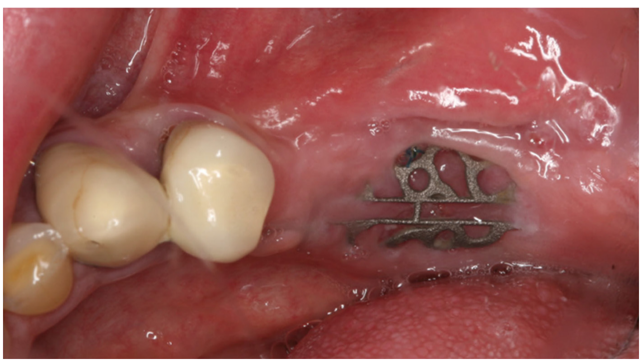

FIGURE 6 Exposed part of a customized titanium mesh after a healing time of 2 months.

5.1 | Intra-oral bone blocks

Oral autologous bone blocks have been successfully used for augmentation of the jaws for decades, even if there is no significant difference in achievable vertical and horizontal gain compared with particulate grafting materials in combination with guided bone regeneration procedures; in accordance, they are mainly used for small to medium alveolar defects (< 3–4 mm).[16,17,156] In one current study, a vertical augmentation above a threshold of 2.55 mm increased the complication rates 5-fold.[17] Nevertheless, block harvesting is associated with relevant donor site morbidity.[13] Although intra-oral onlay grafts from the chin were used earlier in 1965,[157] later on, at the end of the 20th century, ramus grafts became more common.[158,159] This is because of the more extensive harvesting morbidity of chin grafts with common sensitivity disturbances,[160] a problem that seemed to be overestimated according to recent comparative data.[161] Also, permanent nerve disturbance has been described for ramus grafts.[162] Other more extensive studies report no permanent, but 10% temporary, disturbances.[158] For small to medium-sized osseous defects, a limited amount of bone can also be harvested from the zygomatic buttress. Here, specific donor site morbidity mainly constitutes paresthesia and sinusitis.[163] Allogenic bone blocks may be an excellent alternative to oral bone blocks,

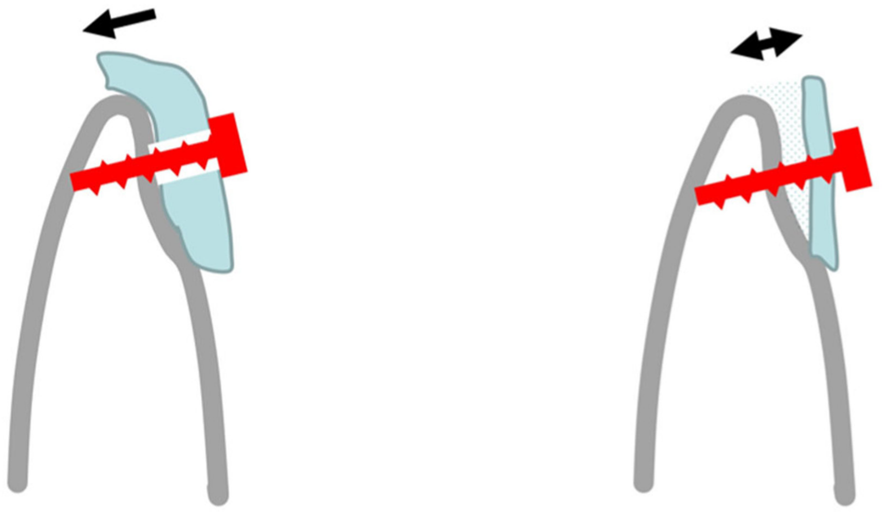

FIGURE 7 Principle of the block technique with a lag screw and primary bone healing, and the shell technique with a positioning screw.

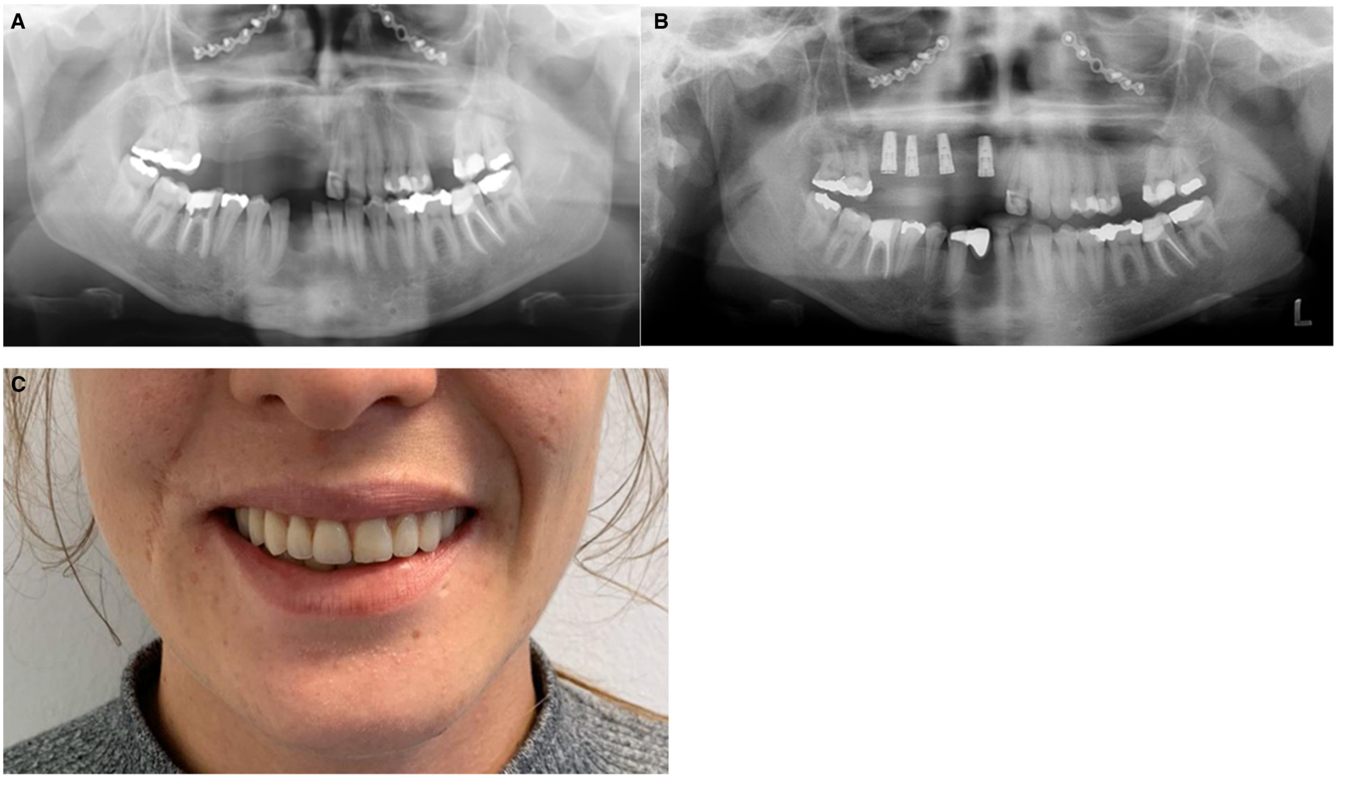

FIGURE 8 Dental restoration after a traffic accident with fractures of the mandible and the midface together with considerable bone loss in a 23-year-old female patient. (A) Panoramic X-ray showing the extent of bone loss in the maxilla; (B) Panoramic X-ray showing the site after insertion of dental implants; and (C) Clinical picture showing the final restoration.

but they have yet to be systematically investigated for large defects.[17,164,165] Compared with the extraoral bone, intra-oral donor sites have many advantages, from surgical access and scar formation to training requirements. Also, histological differences between enchondral iliac crest bone and membranous intra-oral bone have been discussed.[166] Bone resorption for intra-oral ramus grafts was more common in the mandible,[167] and vertical augmentations were more critical than horizontal augmentations.[168] In more minor defects, long-term data showed no difference between the chin and ramus regarding the resorption rate.[169]

5.2 | Extraoral bone blocks

Extraoral bone blocks are usually harvested from sites like the rib, fibula, tibia, and calvaria. Because of its bulky cancellous content with a large volume of bone, and the simple surgical technique required, the anterior part of the iliac crest is often used for augmentation purposes.[170] In a two-team approach, the iliac crest bone can be harvested together with the augmentation procedures. A drawback, however, is the donor site morbidity (mostly pain, sensory alterations, and gait problems)[37,171]; in rare cases, fractures of the iliac crest after bone harvesting are reported. Thus, technical adjustments such as minimizing manipulation of the abductors, avoiding nerve injury, and using hemostatic measures are recommended.[172]

In conclusion, almost 80%–100% of patients reported that they would undergo the same treatment again if necessary.[173] A recent systematic review pointed out that long-term implant survival in sites augmented with iliac crest bone is consistently lower than augmentations with intra-oral grafts.[72] Also, the survival of implants placed in the iliac crest bone has been worse than implants in pristine bone.[83] This may also result from the high resorption rates of the iliac crest bone, especially during the initial postoperative healing phase, indicating the need for early implant placement after 3 months of healing.[86,174] Even so, iliac crest bone is mainly used in advanced cases needing more bone and, therefore, with potentially higher complications (Figure 8).

In summary, intra-oral and extraoral bone grafts have different indications and are used for various rehabilitations; therefore, comparisons may have a particular bias. In continuity-interrupting defects, the success rates of nonvascularized bone are less when compared with vascularized transplants, mainly if immediate reconstruction is intended. Besides, exposure to the oral site may lead to a significantly increased failure rate. Nevertheless, nonvascularized iliac crest bone blocks are still an option for such large defects of the jaws. Here, careful patient selection with an emphasis on the lateral mandible is recommended.[175] The complication rate increases with defect length (especially > 6 cm), lack of rigid fixation, radiotherapy, and infection.[170]

6 | MICROVASCULAR RECONSTRUCTION

For this purpose, autologous vascularized tissue reconstructs extensive tissue defects. At the same time, various augmentation measures can treat more minor imperfections of the mandible and the maxilla, for the large defects needing bone support, that is, after hemimandibulectomy or hemimaxillectomy. Various augmentation measures can be employed for treatment of minor defects of the mandible and the maxilla. However, for large defects needing significant bone support, such as after (hemi)mandibulectomy or (hemi)maxillectomy, microvascular grafts have been recommended. They provide immediate vascular supply to the transplanted bone and soft tissue, resulting in fast healing and resistance to infection and radiation effects. Flap harvesting and its defined vasculature, and re-suturing of the transplants' vessels to vessels near the recipient bed, are needed. These techniques require advanced skills, technology, infrastructure, and materials.[170] However, relevant donor site morbidity, a notable rate of flap complications, including transplant losses, were described.[176–178]

Mostly, grafts from the fibula, the iliac crest, and the scapula are used for bone reconstruction of large bone defects. Each donor site offers unique characteristics, including of large bone defects and soft tissue, quality, and specific donor site morbidity. The fibula flap currently dominates mandibular and maxillary reconstruction with its considerable length of up to 25 cm, its long and wide vascular pedicle, and its location allowing a two-team approach (Figure 9A–E).[179] First, it will enable dental implant placement with subsequent occlusion (even if there is a discrepancy in height), mastication, and speech; second, its donor site morbidity is described as low (mainly ankle instability, stiffness, and sensory deficits).[180]

The fibula can be harvested with soft tissue (mainly skin and muscle), facilitating oral or extraoral reconstruction. The potential drawbacks are a required three-vessel flow of the leg and a thin skin paddle.[181] The iliac crest also offers enough bone (10–16 cm) for complete maxillary and mandibular reconstruction. Still, it is mainly advocated for the maxilla allowing restoration of the bone and simultaneous oronasal separation and intranasal lining.[182] However, the donor site morbidity of the iliac crest flap is high (mostly postoperative hernias), the flap is bulky, and the skin paddle is unreliable.[181] The scapula free flap is also well established for mandibular and maxillary reconstruction. Its advantages lie in an additional large volume of soft tissue, the possibility to combine more than one flap using the same vascular system, and its low morbidity (mostly restriction of shoulder motion), which is reported to be the lowest when compared with the fibula, iliac, and radial forearm flap.[183] A significant disadvantage is the necessity to reposition the patient for flap harvesting. Accordingly, the operative time is extended, and a two-team approach is challenging.

Traditional free-hand techniques have been replaced by virtual planning and computer-aided surgery with personalized devices, such as guide-based osteotomies, for the microvascular reconstruction of bony segments. In brief, this process includes planning, modeling, surgical, and postoperative evaluation phases.[184] For planning and preoperative manufacturing via computer-aided design and computer-aided manufacturing, usually a computed tomography scan of the recipient and the donor site is obtained that is converted into a three-dimensional standard tessellation language file format. The computer-aided design/computer-aided manufacturing workflow for modeling allows the preoperative definition of cutting paths and angles at the resection site and of the graft, as well as the shape of the osteosynthesis material.[185,186] This process can either be done via commercial platforms or the clinic itself, depending on the available resources. On the one hand, this increases accuracy and reduces operation times.[186] On the other hand, intraoperative alterations of the surgical plan might be complex, and computer-aided surgery adds high additional costs.[187,188]

7 | ALTERNATIVES

7.1 | Alloplastic reconstruction

Continuity-interrupting mandibular defects have always been problematic, and autologous (simultaneous) reconstruction is the up-to-date standard therapy.[188] However, not all patients might be suitable for bony reconstruction, either nonvascular or microvascular.[189] Alloplastic reconstruction with rigid osteosynthesis plates is a treatment alternative in those cases, leading to a 40%–60% survival rate after 5 years, with most complications occurring within the first year.[30,190,191] Even so, dehiscence of the soft tissue, loosened screws and fractures of the plates are common.[30,191] Wound infections are known to increase the risk of plate exposure by 6.3% (Figures 10 and 11).[192]

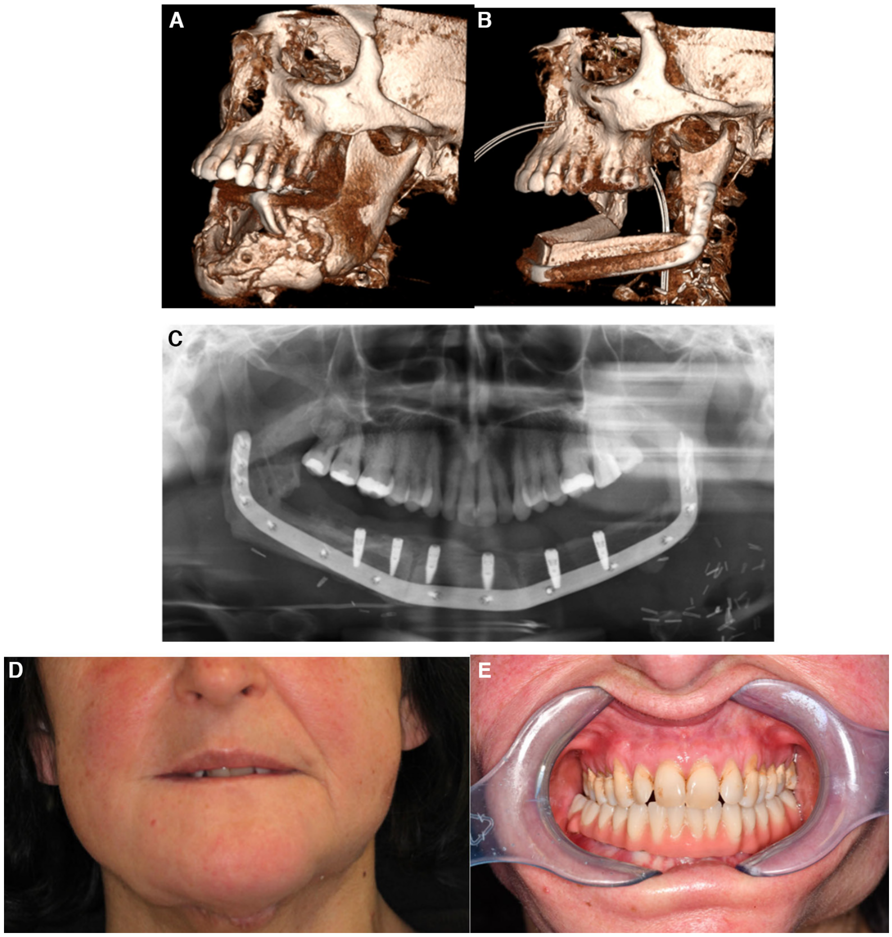

FIGURE 9 Female patient with vast destruction of the mandible because of medication-related osteonecrosis of the jaws. (A) 3D reconstruction of the preoperative CT scan. The bone was removed, and primary reconstruction with a fibula-free flap was carried out. (B) 3D reconstruction of a CT scan after fibula flap transfer. (C) Panoramic X-ray after insertion of dental implants. (D and E) Clinical photographs of the final result. 3D, three-dimensional; CT, computerized tomography.

FIGURE 10 Extraoral perforation of an alloplastic reconstruction plate.

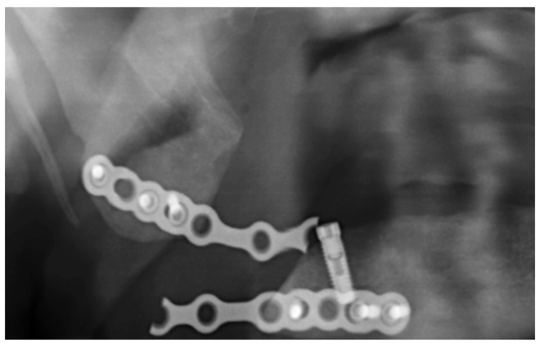

FIGURE 11 Panoramic X-ray of a fractured alloplastic reconstruction plate.

The influence of radiation on the plate complication rate is still controversial, as some researchers found a correlation, while others did not.[191,193–195] With large bone defects (>10 teeth units), involvement of the mandibular midline and smoking seem to influence the occurrence of complications.[30,189–191,193,196,197] Patient-specific reconstruction plates are also used. With those, no further bending is necessary, and areas with high-stress levels can be avoided because of finite element analysis in the planning phase.[198] Because case series also show high failure rates (3/7[199]), more studies are needed. In addition, current concepts of alloplastic reconstruction allow essential functions, but dental restoration might be challenging. If this is the primary aim, osseous reconstruction is needed.

7.2 | Zygomatic implants

At the time of the first description of zygomatic implants, they were used in patients after maxillectomies to restore function and esthetics. As a result, 52 zygomatic implants were reported with a success rate of 96% and a follow-up period of more than 5 years.[200] Since then, various modifications in materials and techniques have been described, also leading to a safe and reliable treatment option for patients with an atrophic upper jaw.[201–203] Overall, current reviews indicate cumulative survival rates for zygomatic implants of more than 95% with follow-up periods of more than 5 years.[203–206] Patients rehabilitated with zygomatic implant-supported prosthetic superstructures report significant improvements in oral quality of life and overall satisfaction (Figure 12).[207]

Compared with traditional implant treatment of the atrophic maxilla, the most notable advantage of augmentation-free zygomatic implant placement is immediate loading to restore the patient's oral function and esthetics after surgery.[208,209] In the literature, a prevalence of 22%–90% is given for immediate loading, with more recent studies showing a clear trend toward immediate restoration without significant differences in implant survival.[210,211] Compared with traditional implants, zygomatic implants require experienced surgeons and prosthodontists to successfully perform this treatment at the highest level. In addition, the placement of zygomatic implants impressively demonstrates the benefit of navigated surgery, which should be seen here as a reliable approach to improving accuracy and avoiding surgical complications.[212] However, it must be noted that using zygomatic implants also carries risks, such as the development of maxillary sinusitis, oroantral fistulas, infraorbital paresthesia, and difficult prosthetic fitting.

7.3 | Obturators

Depending on the size and geometry of the defects, the therapeutic options as well as the number and distribution of the remaining teeth, an obturator may retain and seal the defect with or even without other implants, including elements such as locator,[213] bar,[214] telescopic attachments,[215,216] or different complex superstructures.[216] Considering the risks and costs of reconstructive surgery, this appears to be the preferred treatment modality for many patients after maxillectomy that improves masticatory performance and esthetics[217]; Buurman et al.[217] reported on 11 patients with reconstructed maxilla and compared those with nine obturator patients. They did not show significant differences in masticatory performance or oral health-related quality of life. Besides, in oncological cases, easy access to the resection defect offers advantages in follow-up examinations (Figure 13).

7.4 | Distraction

Distraction osteogenesis was initially described for mandibular deficiencies but has also been used in cases of maxillary hypoplasia.[218–220] It consists of the phases osteotomy, latency, distraction, and consolidation.[221] During distraction osteogenesis, new bone formation occurs between the two segments, continuing until the callus tissue gradually distracts. Accordingly, a new bone will be formed parallel to the distractions' vectors.[222] Distraction osteogenesis is mainly used to correct congenital or acquired craniomaxillofacial deformities. The literature on the reconstruction of defects of the jaw mainly consists of cases or case series and small comparative studies, in which vertical gains of up to 15 mm together with progressive elongation of surrounding soft tissues were described.[223–226] Overall, distraction osteogenesis is reliable with good clinical results. However, several drawbacks have to be taken into consideration as distraction osteogenesis. Distraction osteogenesis may not simultaneously allow the correction of horizontal and vertical deficiencies, and the dimensions of the osteotomies and the distraction devices may limit its use. Besides, fractured devices and problems with the planned vectors may occur. Lastly, the device usually needs removal after the consolidation phase.

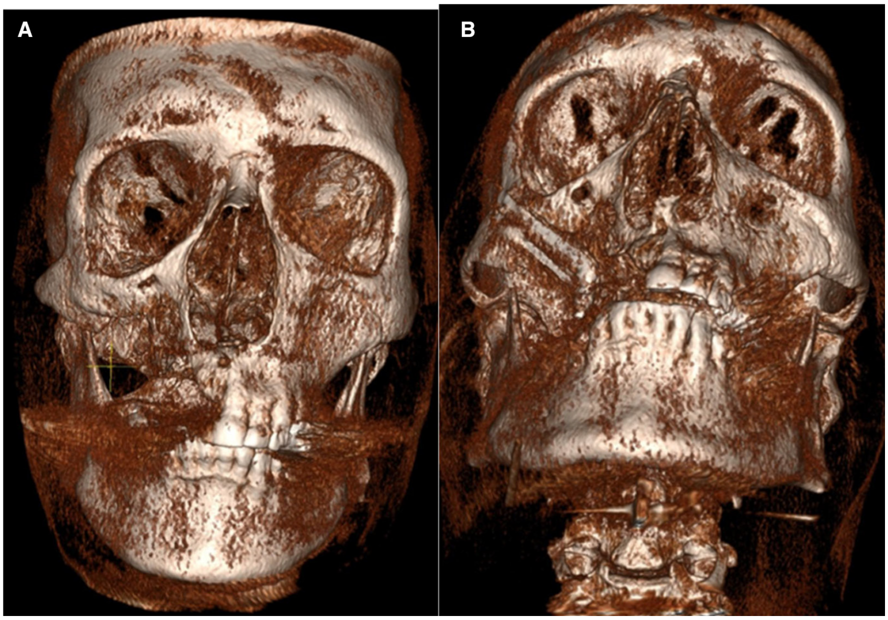

FIGURE 12 Patient with a defect after resection of a benign tumor of the maxilla. He decided against microvascular reconstruction and for reconstruction using zygomatic implants. (A) 3D reconstruction of the preoperative CT scan; (B) 3D reconstruction of the postoperative CT scan after the insertion of two zygomatic implants. 3D, three-dimensional; CT, computerized tomography.

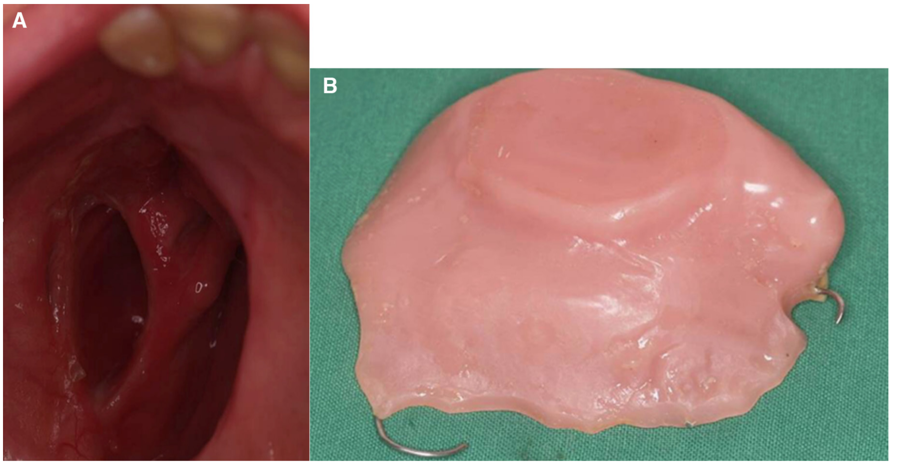

FIGURE 13 Clinical picture of (A) A maxillary defect; and (B) The corresponding obturator prosthesis.

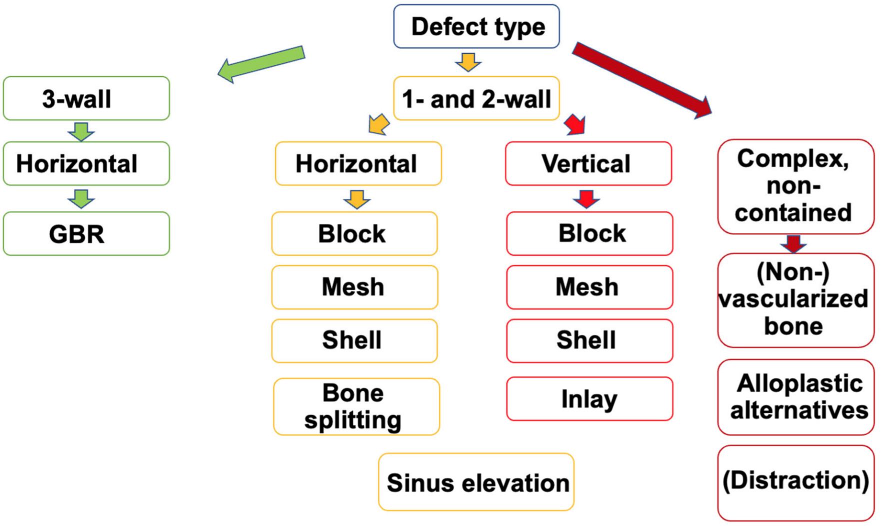

FIGURE 14 Subjective decision tree for extensive maxillomandibular reconstructions. GBR, guided bone regeneration.

8 | CLINICAL IMPLICATIONS

- The planning phase should consider the vitality, regenerative capacity of the recipient bone bed, soft tissue coverage, and patient-specific medical conditions.
- Larger defects and/or defects in compromised patients usually require extraoral autologous grafts, either nonvascularized or vascularized.
- Stabilization of particulated grafts can rely on different technologies (membranes/meshes/shells).
- In selected cases, alternatives to osseous reconstruction (dimension-reduced implants, zygomatic implants, obturators, and alloplastic reconstructions) may be considered.
- Three-dimensional planning options allow analysis, choice of treatment options, patient information, and prefabrication of templates

9 | CONCLUDING REMARKS

The reconstruction of large maxillomandibular defects is a challenge that has been much discussed over the last few decades. Each procedure and situation needs clinical analysis and informed consent for clinical decision-making as there is no clear evidence of a favorable technique and material for reconstruction. A subjective decision tree is demonstrated in Figure 14. Clinical decision-making includes local/systemic factors and incision designs, but the choice of material, grafting technique, and donor site morbidity is highly relevant. Whereas stabilization of particulated grafts—that is, via stable mechanical meshes or shells—might allow a horizontal and vertical augmentation of more than 3–4 mm, larger defects usually need extraoral harvested autologous bone blocks. The anterior iliac crest is often used for nonvascularized augmentation, whereas significant defects requiring bone support need microvascular reconstruction. For this purpose, the fibula flap has become the main workhorse, even if other techniques may offer better results, such as morbidity. Recent alternatives that should be considered and discussed with the patient include alloplastic reconstruction using osteosynthesis plates, zygomatic implants, obturators, and distraction osteogenesis.

In addition, traditional free-hand techniques are increasingly being replaced by virtual planning and computer-aided surgery with computer-aided personalized devices, such as guide-based osteotomies and other surgical guides. The combination of virtual/

augmented surgery and tissue engineering might, in the future, expand the reconstructive capabilities.

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CONFLICT OF INTEREST STATEMENT

The authors report no conflict of interest.

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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