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Hypothesis

Reverse Guided Bone Regeneration (R-GBR) Digital Workflow for Atrophic Jaws Rehabilitation

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Abstract: Background: Treating extended alveolar defects is challenging for their irregular shape and lack of hard and soft tissues. Virtual planned guided bone regeneration (GBR) with customized meshes aims to optimize the treatment by reducing the risk of dehiscence. The mucosa characteristics are crucial in preserving the bone graft covering and vitality. **Methods**: Two three-dimensional and extended defects, a mandibular posterior and anterior maxillary atrophy were reconstructed with a particulate graft and a digitally customized scaffold. The workflow entailed merging the pre-operatory clinical related data from intra-oral scanning with the radiologic ones from cone beam-CT. A final ideal prediction of the soft tissue relationship with the implant-borne prosthesis was virtually elaborated, conditioning the design of the titanium membrane fitting the bone defects. **Results**: A good matching between the scaffold and the bone surface was intra-operatory noted; no complications were registered in the first months of healing with complete integrity of the soft tissues above the graft. **Conclusions**: A careful evaluation of the soft tissues and a forecast of their final relationship with the implant and prosthesis can improve digital mesh/membrane manufacturing with a suitable healing process up to implant placement and loading, favoring peri-implant tissue stability over time.

Keywords: virtual planning; GBR; titanium meshes; digital workflow

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1. Introduction

Guided bone regeneration (GBR) with titanium meshes enabled clinicians to treat three-dimensional and extended defects due to the stiffness of their structure, which contains in situ the particulate graft and contrasts the collapse of the overlying soft tissues [1–3]. Digital technology improved this approach, allowing the design and printing of a scaffold that fits the defect to be reconstructed, correlating the bone grafting to what is needed to support the fixtures and reducing surgical timings and discomfort [1,4–6]. Hence, the dehiscence, the significant shortcoming of this technique, seems to be lowered [4,6,7], with >80% bone volume regeneration predictability of what was virtually planned [4,7–9]. Nevertheless, some doubts about the actual standardization of this approach were raised, and the reliability of the digital systems in realizing what is virtually planned is still unclear [2,4]. Indeed, the literature is scarce on patients and the methodology of the studies, with 97–100% implant survival rate up to 30 months of mean follow-up after implant loading [2,4,7]. When the exposure complication is manageable, appearing after about a month since the intervention and without signs of infection, the CAD/CAM GBR approach is reliable in fulfilling what was pre-operatively planned, homogenizing the outcomes [2].

The precision of the virtual project, comparing the starting clinical situation with the ideal prediction of the final result, is a crucial issue. The forecasting of peri-implant mucosa thickness and shape, and its interaction with the abutment and crowns to be reached at the end of treatment, can allow for predicting the surgical or prosthetic correction of the soft tissues before or after the bone reconstruction with a more accurate implant positioning [10]. Static computer-aided implantology (s-CAI) entails coupling the tissue surfaces data from intra- or extra-oral scanning with the radiographic hard tissues information from the CT to guide the seating of the fixtures. This approach obtained better results regarding insertion accuracy than the free-hand one [11]. The starting bone defect extension and the soft tissue characteristics were crucial in conditioning the GBR with membranes and no customized titanium meshes [12], even with a customized protocol [2,13]. Atrophic sites present an impaired mucosa, raising the muscle insertions toward the residual bone ridge and losing keratinized epithelium. The soft tissues can be irregular with different thicknesses, scars due to previous lesions and treatment, or particularly thin and fragile. A correct soft tissue evaluation can condition the flap design, reducing the exposure rate [13]. Furthermore, the passivation of the flap to cover the graft after the muscle detachment and the periosteum releasing cuts entails a vestibule reduction and a lifting of the mouth pavement with the necessity of soft tissue grafting procedures to obtain keratinized peri-implant marginal tissues [2,4,13]. According to a so-called fully digital protocol, two mono-edentulous sites were treated with implant insertion contextual to the bone reconstruction after pre-surgical planning of the ideal soft tissue architecture [14,15]. Another clinical case was managed by evaluating the vestibular mucosa thickness to resolve the horizontal deficit of an edentulous site with surgical soft tissue modification in combination with prosthetics tricks [10].

This paper proposes a modified workflow for manufacturing a mesh/membrane to reconstruct two different extended alveolar defects. This protocol was called "reverse" since the operative phase started after the digital prediction of the final ideal relationship between dental crowns and gingiva, adding the pre-operative clinical situation.

2. Materials and Methods

Two male patients were referred for a fixed prosthetic rehabilitation of their edentulous areas. The general health condition of both subjects did not contraindicate oral surgical procedures.

The clinical intra-oral exam of the first patient showed a left posterior mandible without premolars and molars, lost more than ten years before due to an untreated severe periodontal disease (Figure 1).

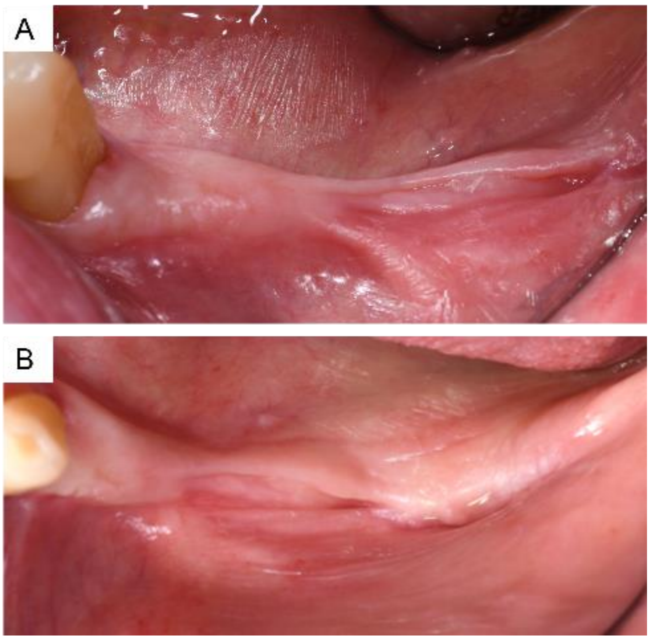

Figure 1. The pre-operative clinical situation of the first patient. Vestibular (**A**) and occlusal (**B**) point of view.

The edentulous lacuna of the second patient corresponded to the upper right pre-molars, canine and incisor area, including the left first incisor, lost for trauma and dental caries and temporarily rehabilitated with a removable residual teeth-supported prosthetic device. The mandibular arch, lacking the first molars, did not present other dental diseases (Figure 2).

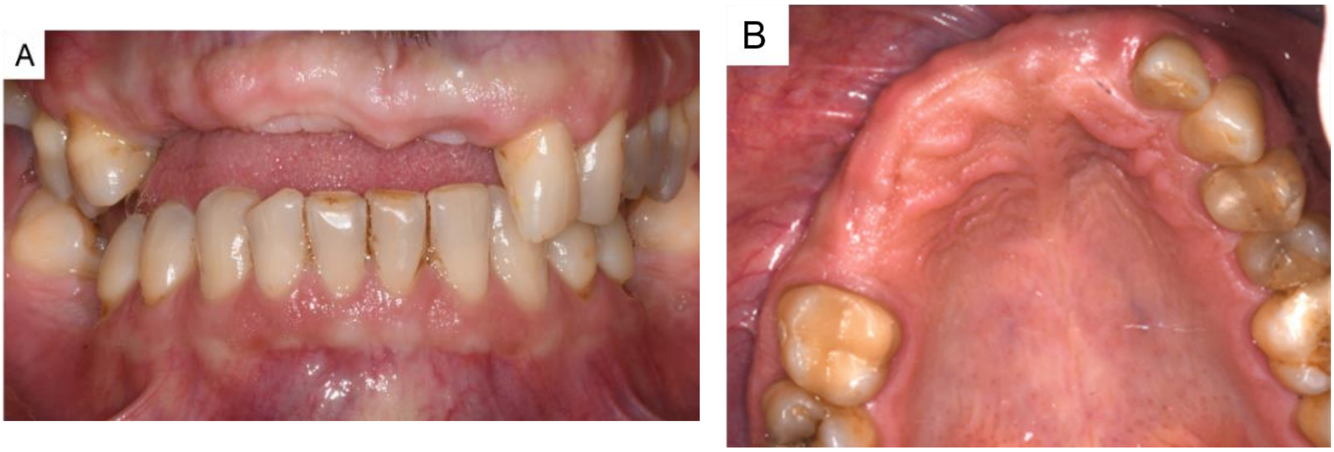

Figure 2. The pre-operative clinical situation of the second patient. Vestibular (**A**) and occlusal (**B**) point of view.

After taking a cone-beam CT (My Ray, Cefla, Imola, Italy), patients underwent scanning of the mouth with an intra-oral scanner (IOS) (iTero Element 2, Align Technology, CA, USA). The DICOM data relative to the bone status were coupled with the standard tessellation language (STL) files relative to the soft tissue characteristics. A virtual wax-up for the correct position of the dental crowns was performed according to the occlusal demands with the opposite dental arch; the crowns were subsequently superimposed to the bone and mucosa representation to identify the discrepancies between the prosthetic and anatomical issues. A simulation of the correct soft tissue final profile was set up, configuring the dimensions and shape of the papillae, and the implants were virtually positioned. The prediction of the bone reconstruction to provide the fixtures with sufficient support came after. The membrane was designed according to the hard tissue volume, position planned and the location of fixation screws. In the first case, it was planned to seat two standard implants in the second pre-molar and second molar location, sustaining a five-crown screw-retained fixed bridge. Implant placement in the canine position was considered after extracting the correspondent mobile tooth. This prosthetic solution entailed a vertical and horizontal bone regeneration of about 8 and 11 mm, respectively, in the molar zone and about 10 mm of thickness in correspondence to the second pre-molar location showing a knife-edge bone ridge (Figures 3 and 4).

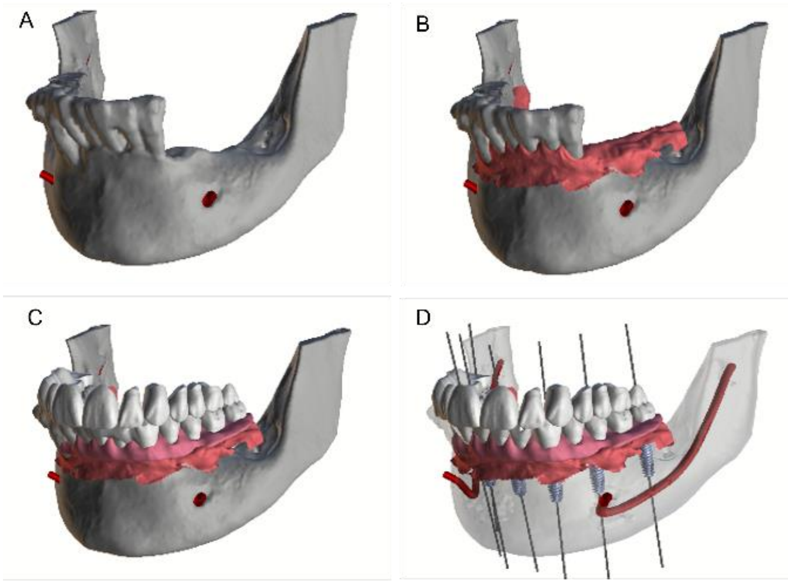

Figure 3. Virtual planning of the first case (phase 1). Bone defect after segmentation from pre-operative CBCT data (**A**); matching with the pre-operative soft tissue profile from the intra-oral scanning (**B**); superimposition of the digital wax-up and set up of the final ideal gingival architecture (**C**); virtual positioning of the fixtures (**D**).

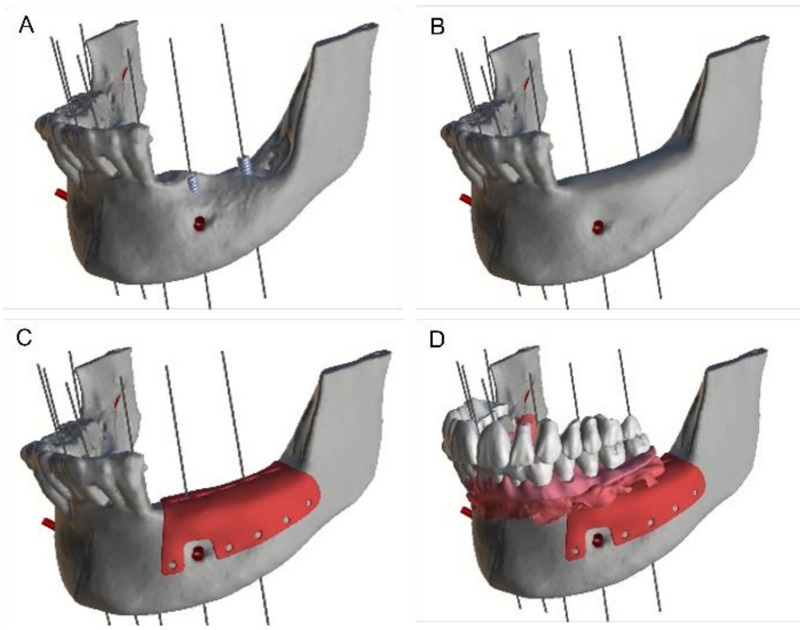

Figure 4. Virtual planning of the first case (phase 2). Ideal choice of the fixtures position and dimensions (**A**); simulation of the bone volume regeneration according to the final result prediction (**B**) and titanium membrane design (**C**,**D**).

The second case showed a vertical and horizontal bone deficit, with a residual bone ridge defining an extended fenestration. The digital wax-up for the correct crown position, the soft tissue ideal profile and the consequent implant locations guided the bone volume assessment and the relative mesh dimensions and shape (Figure 5).

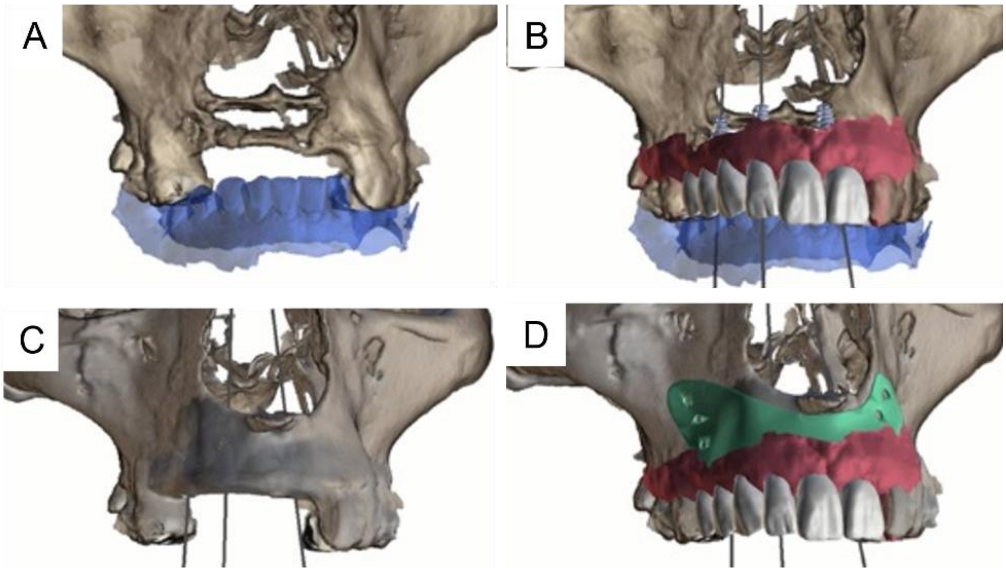

Figure 5. Virtual planning of the second case. Bone status after segmentation from pre-operative CBCT data coupled with the inferior arcade profile from STL data (**A**); the final prediction of rehabilitation according to the simulated ideal prosthetic and gingival profile (**B**); simulation of the necessary bone volume (**C**); the membrane design according to bone volume and final mucosal and prosthetic result (**D**).

Three standard implants were planned to be seated in the second premolar, right lateral and left central incisors location, supporting a six-crown screw-retained fixed bridge with a required bone reconstruction of about 4 mm and 8 mm in height and width, respectively. The virtual mesh/membrane, saved in STL format, was 3D-printed using digital machine laser sintering (DMLS) without macropores and a few fissures in correspondence to its coronal portion.

The same oral surgeon performed the surgical procedures in a dental office under local anesthesia. The bone defects were completely exposed after carefully raising a full-thickness trapezoidal buccal flap after a mid-crestal, two vertical releasing incisions and the detachment of a lingual/palatal flap. The flaps were coronally elongated by releasing incisions and dissection of the periosteum to obtain a complete passive closure on the mesh. Subsequently, bone chips from the buccal surface of the bone close to the defect were scraped with a bone collector. The autologous bone was mixed with a freeze-dried heterologous one (Osteobiol, Gen-Oss, Tecnoss, Turin, Italy) in a 70/30 ratio. The particulate graft was put to fill the deficit above the mesh (3DiFiC, Perugia, Italy) until its perfect stability and unity with the defect's borders. A suitable membrane fitting to the defect was noted without shifting before and after the graft placement. Three titanium mini-screws (Global D, Brignais, France) buccally stabilized the device in the mandibular defect. Two mini-screws in correspondence with the left lateral wall of the nose and the right molar pillar were inserted in the maxillary case. The flaps, coronally advanced before the graft application, were carefully sutured. Amoxicillin was assumed by the patient (two grams a day for six days) together with a non-steroidal analgesic (ibuprofen). The patients were instructed to avoid brushing on the surgical site, follow a soft diet for three weeks and maintain appropriate oral hygiene, including twice-daily rinsing with 0.2% chlorhexidine.

3. Results

During the post-operative healing period, patients were monitored monthly without complications until now (Figures 6 and 7).

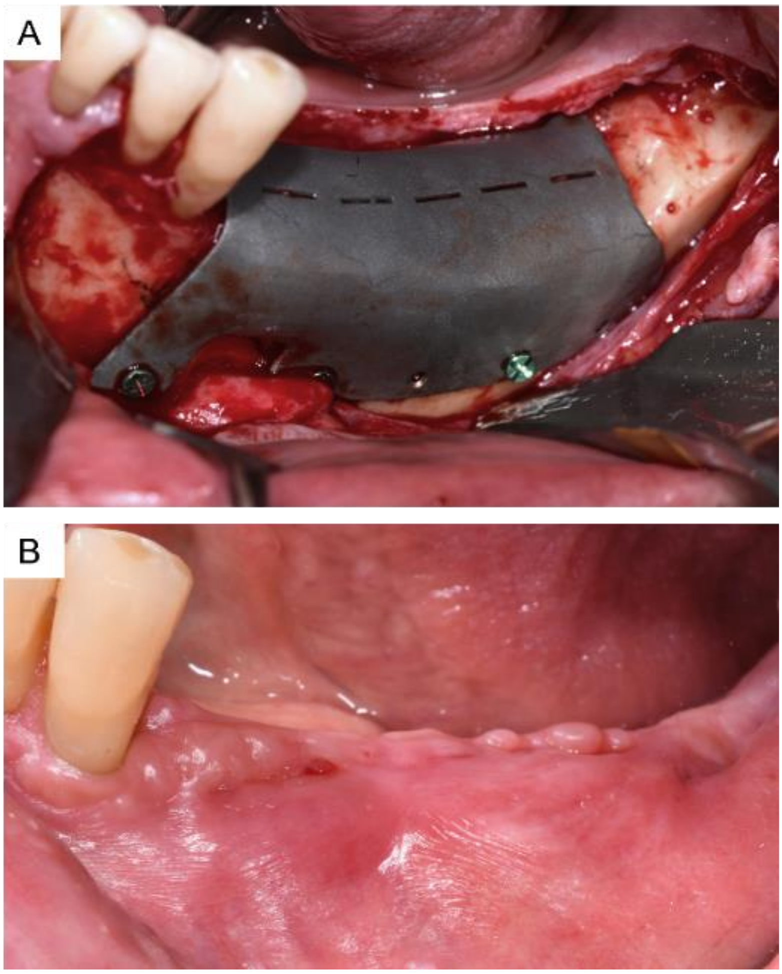

Figure 6. The intra-operatory vision of the fixed membrane (**A**) and clinical situation a month after surgery (**B**) relative to the first case.

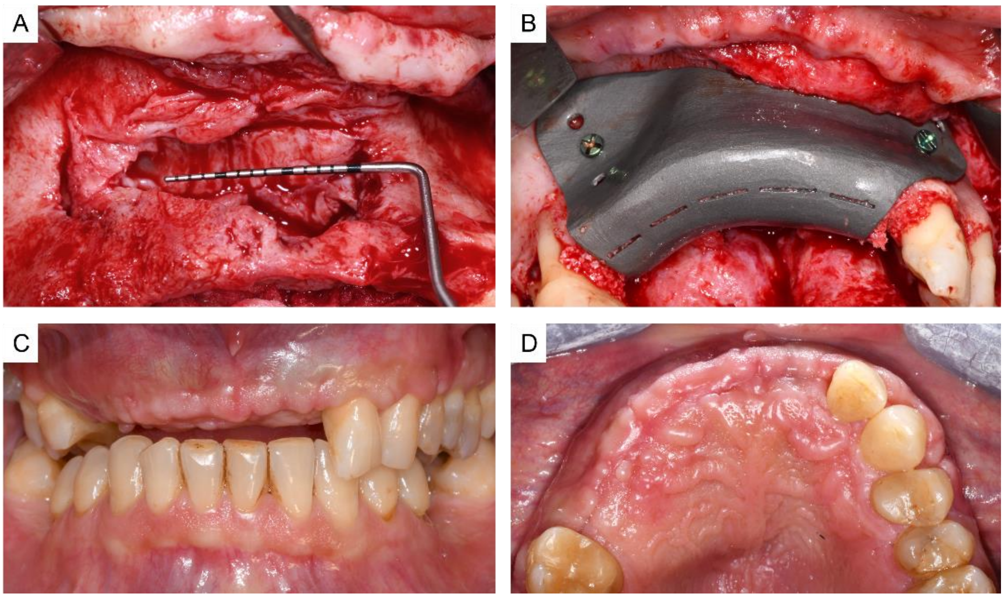

Figure 7. The intra-operatory clinical vision of the defect (**A**), the membrane fixed (**B**) and clinical situation a month after surgery (**C**,**D**).

A new cone-beam CT was taken to verify the bone augmentation and the mesh position after one month of healing, showing a good healing process without the membrane shifting (Figures 8 and 9).

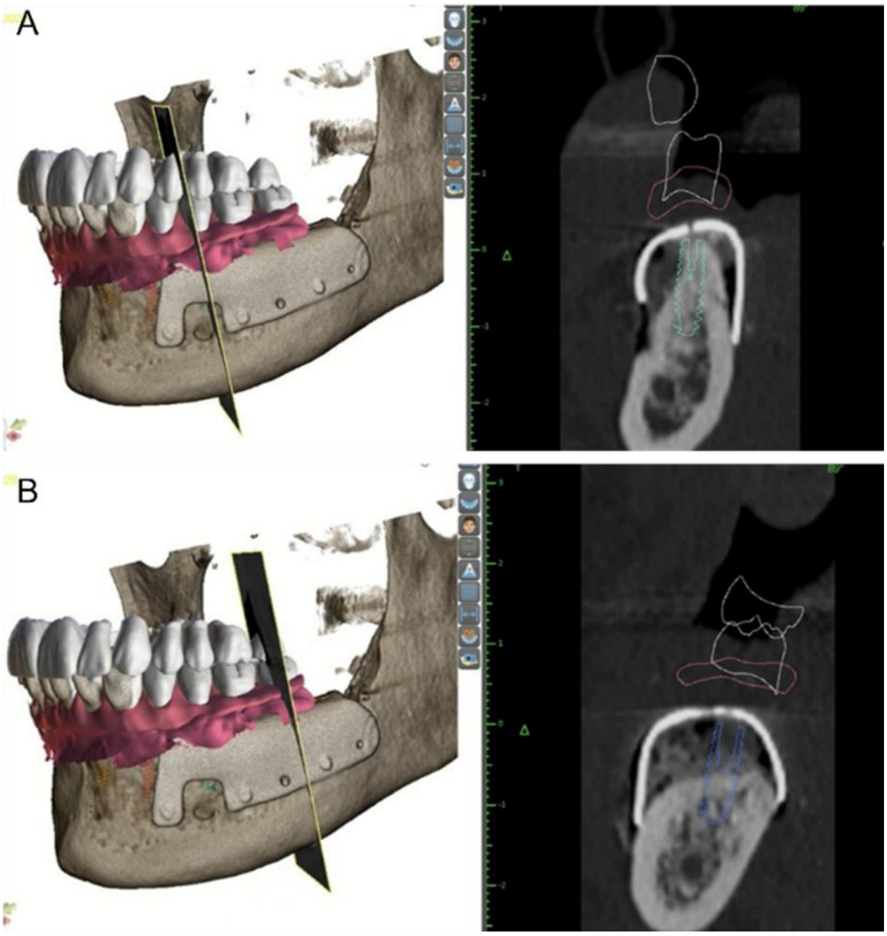

Figure 8. The cross−section CBCT images relative to the second premolar (**A**) and second molar implant location (**B**) in the first case after a month of healing.

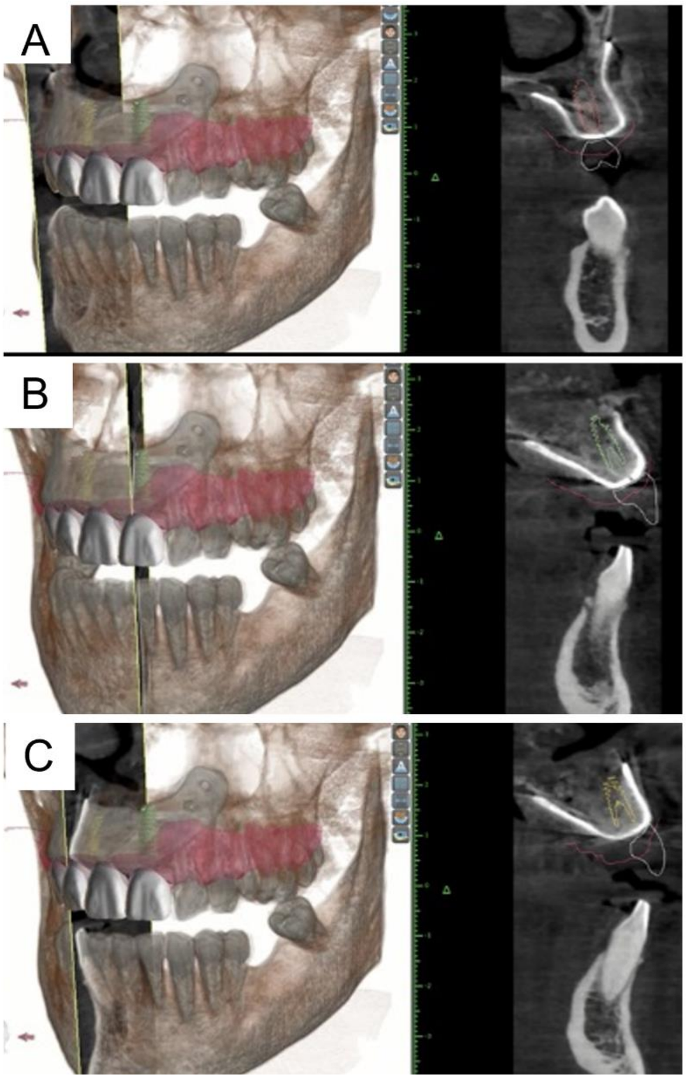

Figure 9. The cross−section CBCT images relative to the second premolar (**A**), right lateral (**B**) and left central incisors (**C**) location in the second case after a month of healing.

4. Discussion

The importance of soft tissues in conditioning a pre-implant reconstructive procedure was widely stated, protecting from infections and supplying nutrients and cells [16–21]. The relationship between the soft and hard tissues and their features conditions the choice of a bone augmentation technical approach or, otherwise, renouncing to it and accepting a prosthetic compromise.

The final prevision of the correct soft tissue profile with the prosthetic crowns can be particularly useful in managing complex alveolar defects with anatomic alterations and wrong occlusal interactions. Hence, the discussion between prosthodontists and patients allows for deciding the more suitable solution for each case. Screw-retained prostheses are today the fixed available solutions for partial edentulous atrophies with aesthetic, functional and hygienic demands [22]. The fixed bridge, without false gingiva and directly connected to the fixtures, requires a precise evaluation of the final soft tissue profile, particularly in the aesthetic zone.

The GBR technique is the most versatile approach, since the particulate graft, maintained by a scaffold, is adaptable to every defect shape. The use of titanium meshes enables the management of more critical defects with fewer infective complications than those with non-resorbable membranes, albeit a 0–68.9% of the reported exposure range [17,18,23].

The literature reports 89.9% implant success up to three years of follow-up [2]. The digital manufacturing of the titanium mesh should have homogenized the final complications and implant success results. However, a considerable variation of reported outcomes poses a few questions. Chiapasco et al. and Cucchi et al. recorded only 11 out of 53 and 1 out of 10 cases of dehiscences [4,7], while Ciocca et al. reported 66% post-operative exposure morbidity in nine patients [1]. Two authors reported 25% exposures, 16% minimal, 7% "like one tooth width" and 1.5% complete, without finding any correlation between these and the soft tissue management, thickness or mesh size [13]. Hartman et al. (2019), on 70 dis-homogeneous treated sites, reported 37% exposures [24]. Sumida et al. did not find a significant difference in mucosal dehiscence and infection between custom mesh and conventional [6]. The mean vertical bone gain reported by studies adopting linear measurements ranges from 3.9 mm [1] to 6.5 mm [25], with a maximum of 8.9 mm [4]. The width augmentation goes from 5.5 [25] to 6.35 [4] with a maximum of 11.5. These data were not compared with the virtually planned ones. Similar results were obtained with the no-digital technique, with a linear vertical augmentation mean range of 3.7–5.4 mm in combined defects [26]. Regarding the percentage of regenerated bone volume concerning the planned one, the values go from 65% [2] to 91.9% [4]. Such discrepancies can relate mainly to the different extension and morphology of the treated defects [12], often considered together in the same trial, or to the operators' experience in surgically managing the soft tissues, or, on the other hand, the precision and reliability of the digital systems and the confidence of the operator in using such a technology. Treating a homogeneous cohort of nineteen extended three-dimensional atrophies, Lizio et al. obtained five complete failures due to early infection and graft loss; nevertheless, once passed the first critical six weeks, the reliability of the technique in terms of osseous regeneration came to 88% [2].

The operator's surgical skill seems to maintain its importance, albeit, with the digital approach, a single expert surgeon obtained a lower exposure level (10–25%) [7,13] than in the two trials with more operators (52.3–66%) [1,2]. Hartman and Seiler adopted different flap designs, attributing the low rate of early exposure obtained to proper management of the mucosa. These authors warned about scars from inflammation processes or previous surgeries [13].

Regarding the reliability in reproducing what is virtually planned, Li et al. recorded +19.3% regenerated bone volume under the mesh compared with what was digitally planned, probably due to an upward shifting of the device. In addition, the same authors referred to a mean value of 0.59 ± 0.47 mm of mesh border deviation among the virtual and the post-GBR situation, up to a 3.4 mm maximum discrepancy [8]. Lizio et al. reported 82% matching between the digital mesh position and the surgical one from the post-operative CT data, confirming a statistically significant mesh fitting to the bone defect independent from the operator but with a relevant range (53.3% to 100%) of incongruity [2]. No other objective evaluation of this issue was reported, even if, in general, the project resulted in the number, dimensions and positions of the fixtures and prosthetic finalization [1,4,7–9,13].

From all the above considerations comes the necessity to enhance digital workflow by controlling as many elements as possible to optimize the amount and distribution of bone reconstruction. It is worth noting that a digital customization flowchart reduces the operation times and the number of fixation screws. However, it is more expensive than the traditional procedure and does not allow intra-operative correction [2,13]. In our opinion, the two reported cases required particular attention to the highly correlated risk of failure. The posterior mandibular site, difficult because of the presence of the mental foramen and the mylohyoid muscle on the lingual side, and the maxillary one, with critical aesthetic implications, forced us not to consider only the bone tissue alteration.

The mesh design in the present report did not contemplate macropores, apart from a few fissures in the portion of the device in contact with the most coronal ridge of the residual crest. This particular structure, contrasting with the recent tendency, aims to reduce the fibrotic tissue's invasion of the regenerative space with a minimal periosteum-like tissue formation. This fibrosis, helpful in preventing the graft from infection in case of dehiscence [17], reduces bone formation and complicates the mesh removal in the implant placement phase. Accurate planning of the regenerative space starting from the ideal prosthetic finalization could better reduce the risk of exposures and, consequently, the relevance of the fibrotic tissue protecting role, whose unpredictable amount and structural characteristics complicate the virtual plan fulfilment.

Indeed, no trial adopted a "titanium membrane" without holes. Apart from a few hypotheses [27], the design, thickness, pore dimensions and numbers and the treatment of the meshes surface are not demonstrated to condition the procedure. Recently, an in vivo study reported that the microporous structure of titanium mesh enhanced angiogenesis from periosteum in vertical ridge augmentation better than macro, associated with enhanced vascular permeability and osteoconductive capabilities [28]. Van Steenberghe et al. reported that about ten consecutive patients had undergone GBR with an occlusive titanium barrier, allowing the insertion of 33 fixtures to bear a fixed prosthesis. The peri-implant bone level was stable for up to 5 years of follow-up. Animal and clinical data showed the great potential of an occlusive titanium barrier, which further underlines the importance of soft tissue evaluation and surgical management [29].

In addition to the CBCT-related data quality and the printing system, this approach depends on the STL files' accuracy and the precision of the software in coupling them [11,30,31]. The precision of the extra- or intra-oral scanners was reported in different trials [32–34]. The patient clinical situation and the operator's technical skill condition the intraoral scanning, while impression distorts the reliability of extra-oral scanner data [34]. Eventually, the manufacturing process and the structure of the membrane are relevant in reproducing what is planned [11]. Several studies on s-CAI reported a greater accuracy in implant placement compared with the free-hand procedure, with a reduction in the importance of operative expertise [30,31,34]. This outcome appears more interesting in flapless procedures, where soft tissue thickness and superficial characteristics are more important [35]. A fully computerized procedure appears to be more precise than a partially computerized one [34]. Hence, the present case report aims to stimulate the research toward more and more precise customization of the titanium barrier to improve the reconstructive approach, particularly in hugely atrophic sites. The following evaluation step will be the superimposition of the data related to the pre-implant CBCT to the pre-operative project to digitally verify the membrane fitting with the surgical site beyond the surgeon's perception. According to the outcomes obtained over time with the presented cases, at least for the pre-prosthetic phase, a survey will be accomplished after the final approval of the ethics committee.

5. Conclusions

This preliminary reported protocol enabled surgically managing two complex and extended alveolar defects without intra-operatory complications, a perfect fitting of the mesh and reduced operative timings and no complications up to one month after surgery. The completion of the treatment will confirm the goodness of this fully planned digital approach.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki. Ethical review is not applicable as preliminary cases report with a validated technique.

Informed Consent Statement: Written informed consent has been obtained from the patients to publish this paper.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

GBR	Guided Bone Regeneration
3D	Three-Dimensional
CAD/CAM	Computer-Aided Design/Computer-Aided Manufacturing
CBCT	Cone-Beam Computerized Tomography
CT	Computerized Tomography
STL	Standard Tessellation Language
CA (s-CAI; d-CAI)	Computer-Aided Implantology (static and dynamic)
DMLS	Digital Machine Laser Sintering

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