Reconstruction of Maxillofacial Osseous Defects with Computer-Aided Designed/Computer-Aided Manufactured Devices

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1. Introduction

Over the past years, virtually planned surgery has been increasingly utilised in maxillofacial reconstructive surgery. The concept of computer-aided surgery uses surgical simulation and three-dimensional (3-D) computer-aided designed/computer-aided manufactured (CAD/CAM) tools such as cutting guides and jigs rather than relying exclusively on intraoperative manual approximation for facial reconstruction [1].

The advantage of virtually planned surgery over conventional surgery has indisputably less deviation between reconstructed and natural bony landmarks [2]. Nevertheless, the amount of time saved by using the CAD/CAM approach is subject to controversy. On the one hand, microsurgical craniofacial reconstruction using computer-assisted techniques, such as for fibula-flap harvesting, has yielded significantly shorter ischemia times even with a larger number of osteotomies compared with conventional techniques [3]. On the other hand, the time savings should be considered in light of the additional time needed to complete the preoperative virtual modeling session, which can take up to an hour. So if saving time were a means of recouping the added cost of the CAD/CAM technique, the overall operative time should not be different from that of the conventional technique [4]. However, no differences between the techniques exist with respect to perioperative and long-term outcomes, length of hospital stay, recipient-site infection, partial and total flap loss, or rate of soft-tissue and bony-tissue revisions [3].

We report herein our experiences using CAD/CAM techniques in five separate cases and discuss them on the basis of recent criteria for the usage of CAD/CAM techniques given in the literature.

2. Materials and methods

2.1. Classification systems of osseous maxillofacial defects

Osseous defects of the maxillofacial region are described using international classification systems. The applied classification of mandibular defects refers to the HLC classification described by Boyd et al. [5]. The *H* represents a defect compromising a lateral segment of any length containing a condyle and not substantially crossing the midline, *L* stands for the same defect but without a condyle, and *C* represents the anterior segment between the incisor foramina. The classification of maxillopalatine defects refers to the classification given by Okay et al. [6]. Class Ia summarizes defects with no involvement of the tooth-bearing alveolus; Class Ib, preservation of both canines; Class II, resection of one canine or less than 50% of the hard palate; Class III, resection of both canines or greater than 50% of the hard palate.

2.2. CAD/CAM technique

The CAD/CAM technique was applied for the reconstruction procedures. An exemplary operational sequence of virtual osseous reconstruction with CAD/CAM technique is given in Figure 1. Planning was performed on 3-D images generated from high-resolution, helical computed tomography (CT) scans of the maxillomandibular region and the chosen donor site, respectively. The patient's natural anatomy was restored virtually by mirroring the unaffected side (case 1 to 4). The mirroring protocol is not possible in defects involving both sides of the mandible or maxilla. Therefore the solution is having a database from other patients which can be imported as a reference (case 5). The selected osseous donor site was virtually harvested, trimmed, and inset using the tools contained in the appropriate planning software of the CAD/CAM tools-providing company (case 1 to 4: MedX, Xilloc Medical B.V., Maastricht, The Netherlands; case 5: ProPlan CMF, Synthes/Materilise, Leuven, Belgium). Patient-specific cutting guides for the donor site, as well as for the recipient site (if applicable), were created using a 3-D printer. The prepared cutting guides should ensure the accurate segmentation and implementation of the harvested bone.

2.3. Subjects

All patients were recruited and treated at the Department of Oral and Maxillofacial Surgery and Plastic Operations. In all cases of applying the CAD/CAM technique, the bony reconstruction was intended to provide a basis for implant loading and prosthetic rehabilitation of the patient. Subjects gave written informed consent to publish their medical records and accompanying images. An overview of the presented cases with applied CAD/CAM technique for maxillofacial reconstruction including their histories, chief complaints, affected sites and types of reconstruction is given in table 1.

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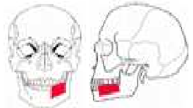
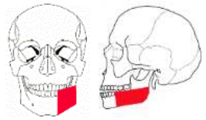
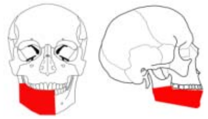
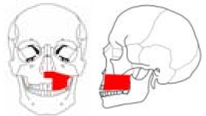
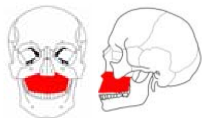
Table 1. Overview of cases with applied CAD/CAM technique for maxillofacial reconstruction.

Case	Age	Gender	History	Chief complains	Affected site	Class	Reconstruction
1	72	M	SCC of the lateral floor of the mouth and alveolar ridge, partial mandibular resection	Missing bony width and height		L	Free iliac crest
2	54	F	Chronic osteomyelitis, mandibular continuity resection	Recurrent facial pain and swelling		L	Vascularised iliac crest and ASIS
3	72	F	SCC of the lateral floor of the mouth, ORN of mandible, mandibular continuity resection	Deviation and severe scaring of lower face		LC	Vascularised two-segment osteomyocutaneous fibula flap
4	43	F	Maxillary ACC, hemimaxillectomy	Wide opening of maxillary sinus and nasal cavity		III	Double Flap technique: vascularised osteomyocutaneous double-barrelled fibula flap and RFF
5	45	M	Toxic induced subtotal maxillary osteonecrosis	Wide opening of maxillary sinus and nasal cavities		III	Vascularised three-segment osteomyocutaneous fibula flap

SCC = Squamous Cell Carcinoma, ASIS = Anterior Superior Iliac Spine, ORN = Osteoradionecrosis, ACC = Adenoidcystic Carcinoma; RFF = Radial Forearm Flap

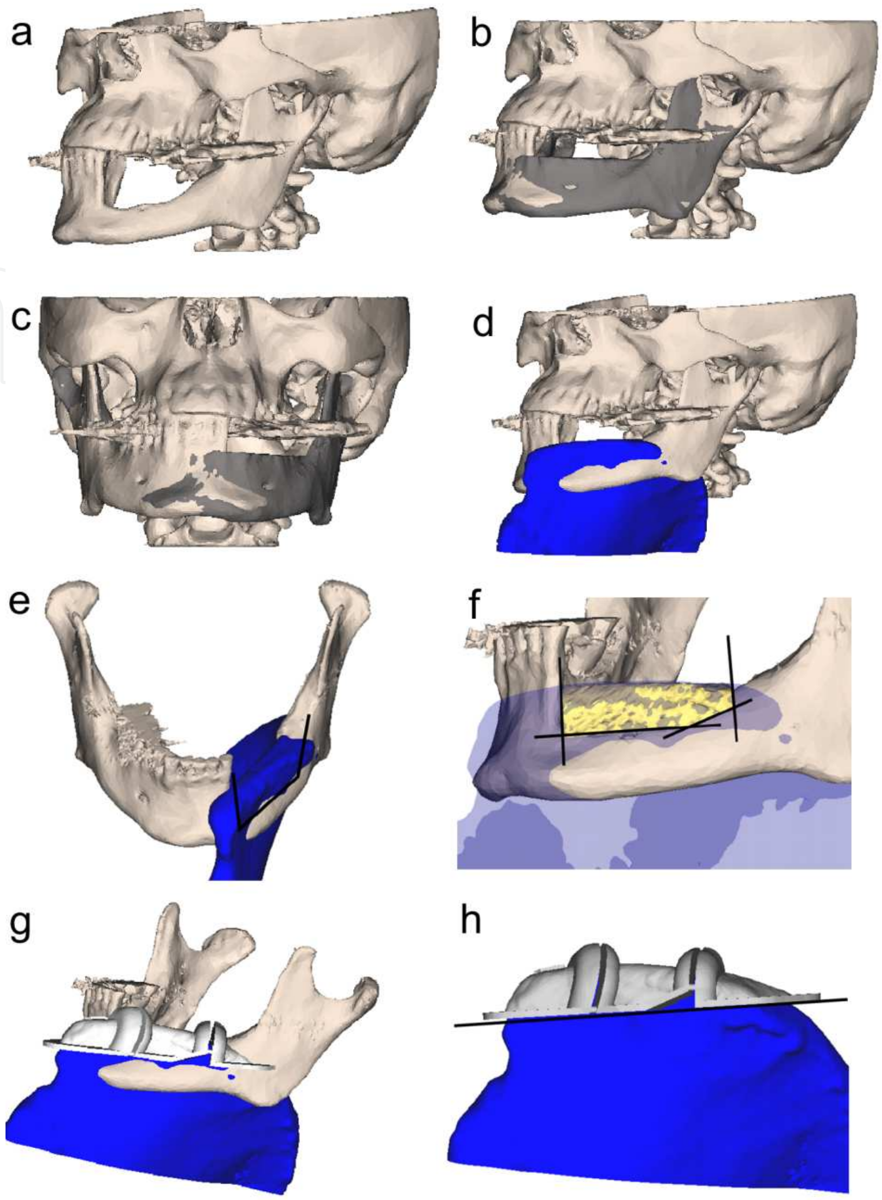


Figure 1. Exemplary operational sequence of virtual osseous reconstruction with CAD/CAM technique. (a) Initial findings in 3-D CT, (b) and (c) Mirroring the unaffected side for virtual reconstruction, (d) Selecting a proper harvesting site by precisely superimposing the virtually reconstructed side, (e) and (f) Virtually harvesting, trimming and insetting of the osseous transplant, (g) and (h) Designing patient-specific cutting guides for 3-D printing.

3. Clinical case studies

3.1. Case 1

A 72-year-old male was admitted to our centre with squamous cell carcinoma (SCC) of the left lateral floor of the mouth and the adjacent alveolar ridge. He underwent tumour resection including partial resection of the left mandible with scarifying of the ipsilateral canine,

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premolars, and molars, leaving a Class L defect. No mandibular resection in continuity was necessary. Hence, it was possible to preserve the inferior alveolar nerve (IAN) and the base of the mandible to ensure stability without osteosynthesis.

One year after primary surgery, reconstruction of the mandible was virtually planned to augment the missing bony width and height (Figure 2). An additional soft tissue transfer was not necessary since the residual soft tissue would provide a sure and tensionless wound closure. Within the intraoperative use of a CAD/CAM cutting guide for harvesting a left iliac crest bone part, the anterior superior iliac spine (ASIS) could be preserved. Using an intraoral approach, we inset the harvested free iliac crest bone and rigidly anchored it with two osteosynthesis platelets (2.0 mm system, Stryker Corp, Freiburg, Germany). On the anterolateral aspect, a space of 1.5 mm was left between the transplant and the preserved alveolar ridge of the mandible. Therefore, it was necessary to bridge this gap with cancellous bone. Both, postsurgical wound healing and further recovery were uneventful.

3.2. Case 2

In a 54-year-old female, chronic osteomyelitis of the left mandible from the premolar region up to the ascending ramus was detected with bone scans consisting of scintigraphy using single-photon-emission computed tomography (SPECT) and CT scans (Figure 3). A recurrent intravenous antibiotic regime with piperacillin 3 × 2 g and sulbactam 3 × 1 g and local decortication did not lead to an enduring remission.

We consequently decided to resect the involved mandibular segments, achieving a Class L defect, and to perform an immediate osseous reconstruction in one operative session. The IAN was already compromised, leaving an anaesthetic area of corresponding ipsilateral skin, mucosa, and lower lip. Virtual planning revealed that the best reconstruction could be obtained using the ipsilateral ASIS and accompanying parts of the iliac crest.

At surgery, CAD/CAM cutting guides were used for mandibular resection, and iliac bone harvesting ensured an exact fit of the osseous reconstruction. Vascular, pedicled iliac bone was harvested, inset, and fixed with osteosynthesis platelets before microvascular anastomoses were done. Following resection of the mandible, the condyle-bearing portion of the mandible immediately rotated clockwise and was repositioned upon inset of the iliac bone flap. No further augmentative features were necessary because the intraoperative findings were in strict accordance with the planned situation. No complications occurred during the postoperative course and no further episodes of inflammatory osteomyelitis were realised during a follow-up of 6 months.

3.3. Case 3

A 72-year-old female suffering from SCC had tumour resection of the anterior and right lateral floor of the mouth. Soft tissue reconstruction was performed with a radial forearm flap (RFF). Postsurgically, necessary radiotherapy led to severe osteoradionecrosis (ORN) of the mandible, compromising the area of the contralateral canine region up to the ipsilateral mandibular

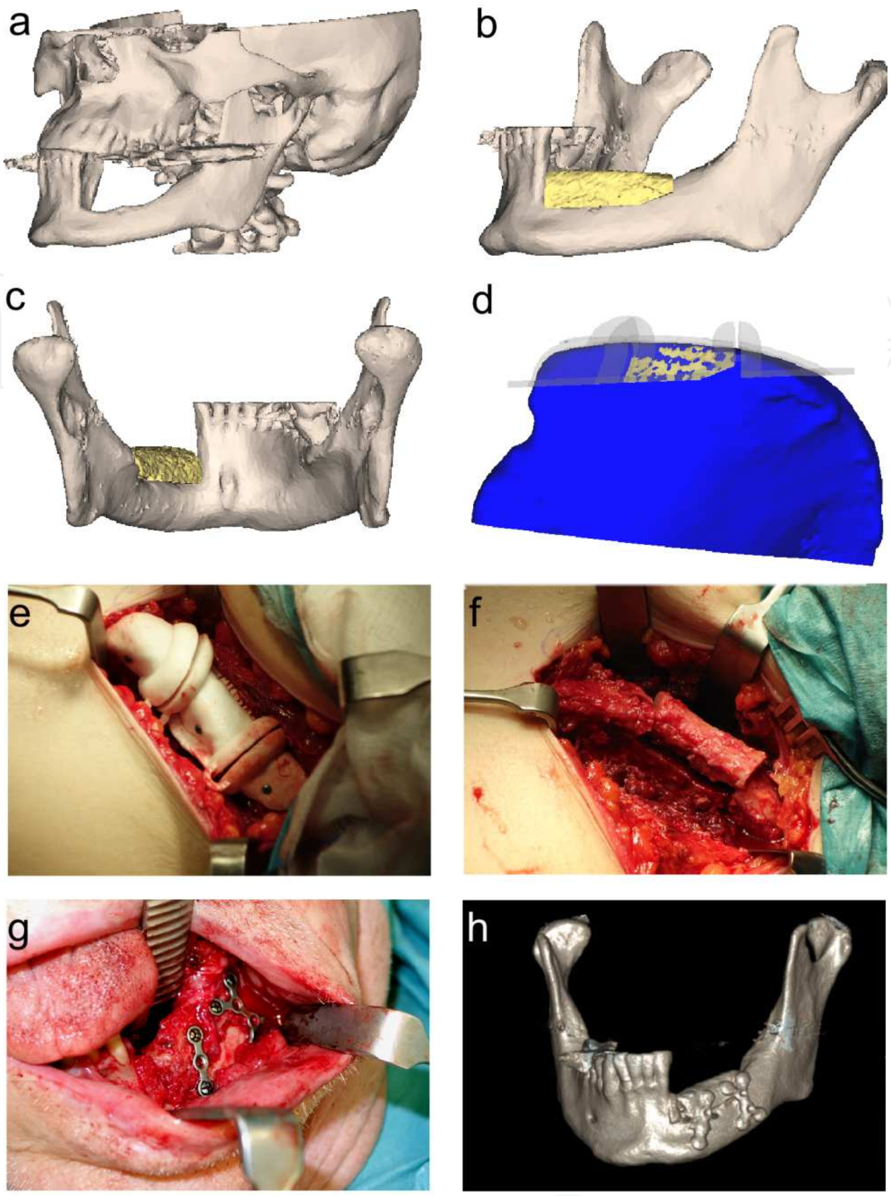

Figure 2. Case 1. (a) 3-D CT shows the left mandibular defect. (b) and (c) Virtual reconstruction of osseous defect. (d) Virtual iliac crest with planned cutting guide and transplant. (e) Intraoperative positioning of the cutting guide. (f) Harvesting of the iliac crest bone. (g) The transplant inset and fixed. (h) Postoperative 3-D CT findings with iliac crest for mandibular augmentation.

angle. The affected parts of the mandible were completely resected without further reconstruction, leaving a class LC defect.

During follow-ups, the patient complained about ipsilateral deviation of the lower face after muscle contraction and scar formation. No applicable prosthetic solution could be devised. After 1 year and without any further evidence of ORN, mandibular reconstruction was planned using CAD/CAM tools for harvesting a vascularised osteomyocutaneous fibula flap (Figure 4). Intraoperative cutting guides for the mandibular stumps were used to assure straight osteotomy lines. Another cutting guide was needed to produce a two-segment fibula

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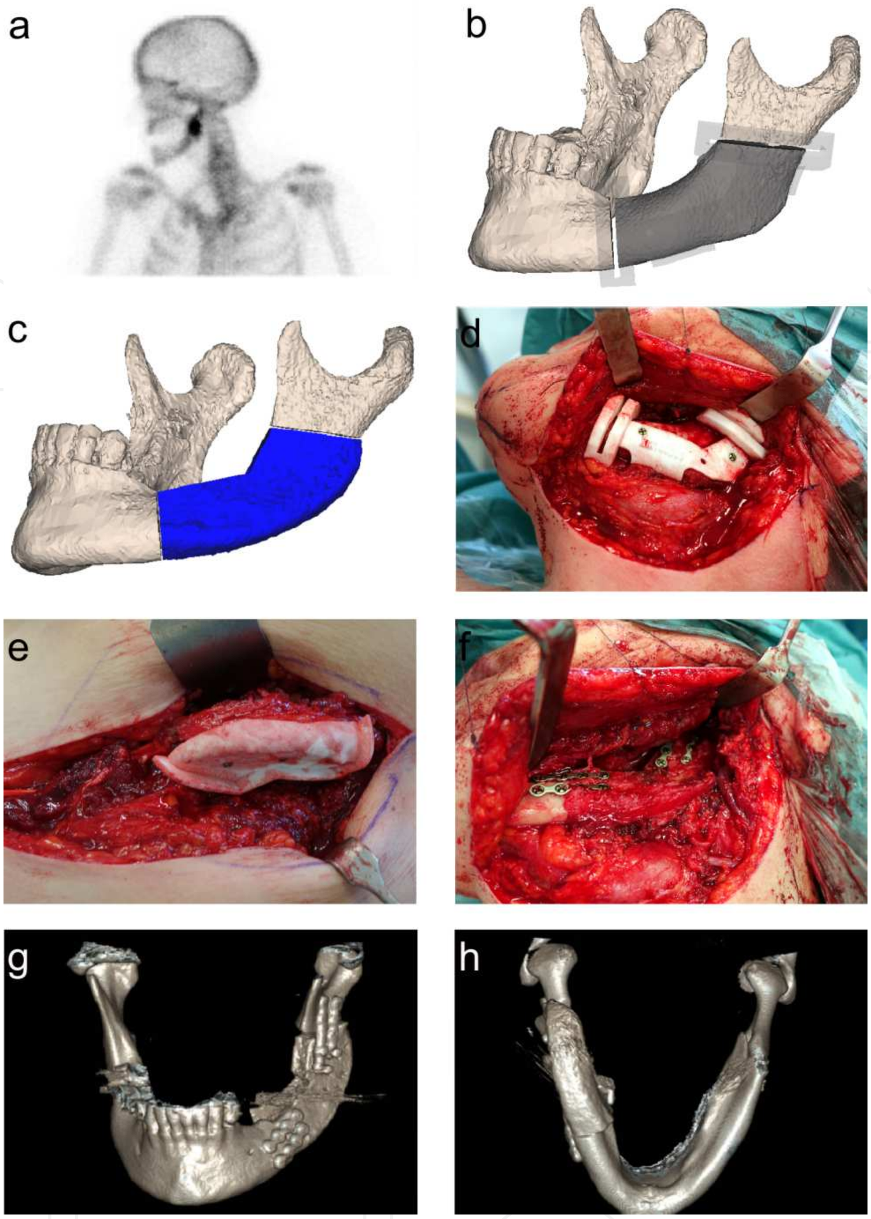

Figure 3. Case 2. (a) SPECT shows osteomyelitis of the left mandible. (b) and (c) Virtual resection and reconstruction of mandible. (d) and (e) Intraoperative positioning of the cutting guides on the mandible and the iliac crest and ASIS. (f) Vascularised iliac bone flap inset and fixed. (g) and (h) Postoperative 3-D CT showing incorporated iliac bone flap.

to reconstruct the mandibular angle, corpus, and the anterior part. A skin paddle containing two septocutaneous perforators was placed extraorally over the chin area to provide volume for the resulting skin defect after dissolving the scars and repositioning the soft tissue chin in the facial midline. Intraorally, the former RFF provided stable soft tissue coverage. The segmented fibula was stabilised and fixed to the prepared mandibular stumps with osteosynthesis platelets before microvascular anastomosis was carried out. The fitting was in accordance with the planned situation, including repositioning both condyles. No trimming or application of cancellous bone was necessary. The wounds healed primarily and the further postsurgical course was uneventful.

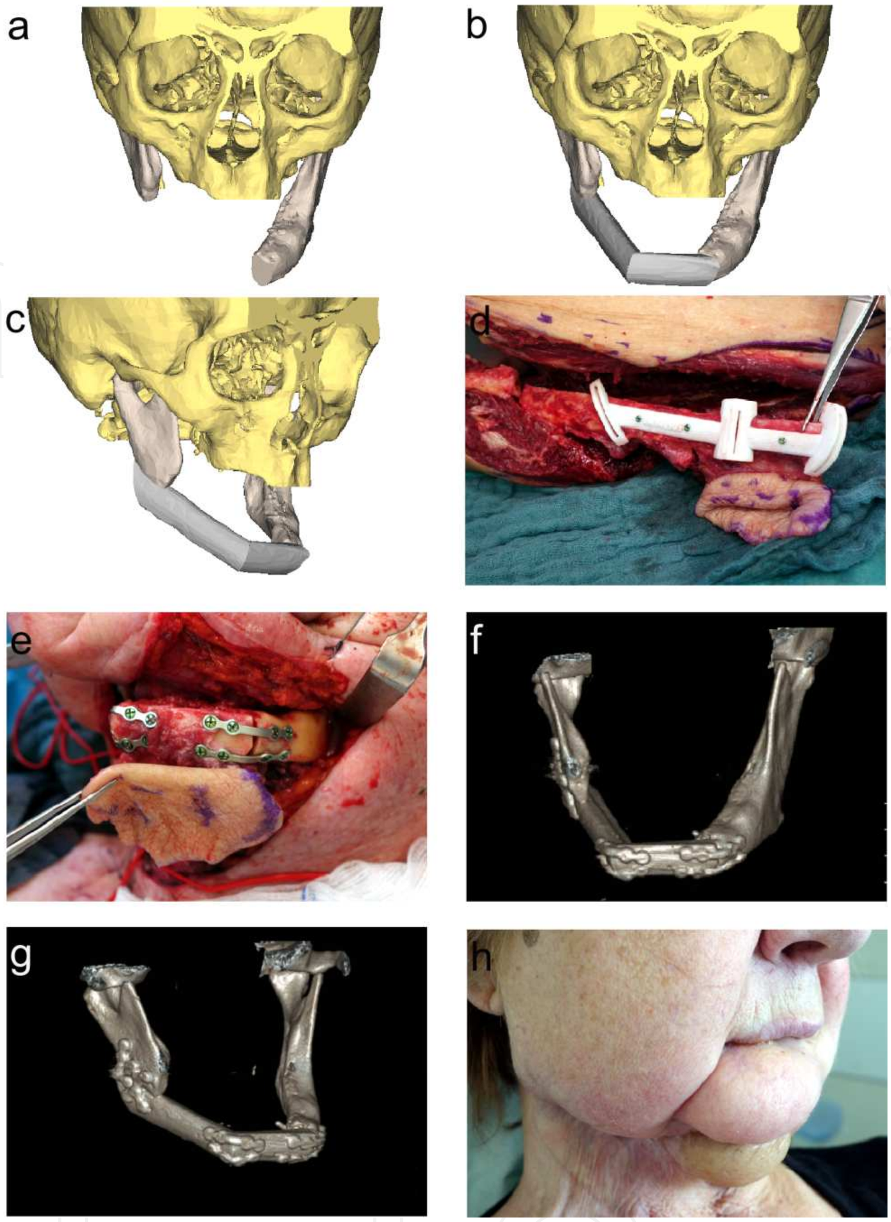

Figure 4. Case 3. (a) Initial mandibular defect in the 3-D CT. (b) and (c) Virtual reconstruction with a two-segment fibula flap. (d) Intraoperative positioning of the fibular cutting guide. (e) Inset of the prepared and osseous segmented osteomyocutaneous fibula flap. (f) and (g) Postoperative 3-D CT of reconstructed mandible. (h) Complete wound healing after 4 weeks.

3.4. Case 4

In a 43-year-old female, an adenoidcystic carcinoma of the left maxilla and hard palate was histologically confirmed. Tumour surgery consisted of a hemimaxillectomy up to the zygomatic arch and resection of the left and part of the right hard palate to achieve clear margins. The maxillary sinus, nasal cavity, and septum were widely exposed, comprising a Class III defect. No primary reconstruction was carried out. Radiotherapy was applied postsurgically, as suggested by the tumour board.

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One year after initial therapy and with no evidence of recurrence, reconstruction was virtually planned and realised by performing a double-flap technique for covering the soft and hard tissue defects (Figure 5). During one operation, a fibula flap, with a wide muscular cuff to provide bulkiness, was harvested. The fibular bone was then segmented using a CAD/CAM cutting guide and prepared as a double-barrelled fibula by folding upward a precisely determined distal portion of the fibula. This technique was chosen to apply the necessary bony height to fill the osseous maxillary resection defect. After osteosynthesis between both fibular parts and between the fibula and the preserved maxilla, microvascular anastomosis was carried out. In the next step, an RFF was harvested to cover the muscle cuff of the fibular flap and to provide adequate soft tissue coverage for the palatal defect. The postoperative course was uncomplicated and both flaps were successfully incorporated.

3.5. Case 5

At first presentation, a 44-year-old male complained of chronic facial pain and nasal outflow of fluid and food for at least two years. Clinical inspection revealed a desolate intraoral situation with osteonecrosis of the nearly edentulous upper jaw and palate with oroantral and oronasal fistulas. After careful inquiry, the patient admitted chronic abuse of alcohol, nicotine and of the illicit drug methamphetamine (MA) for at least 25 years. For the past 20 years, he had synthesized MA for his own consumption and for illegal disposal in his home country. Furthermore, he confessed to extracting teeth himself since he became addicted to MA. After further investigation, a history of bisphosphonate intake for any reason or radiation of the head and face was definitely ruled out. In the last year the patient had successfully completed a drug intervention and rehabilitation program and he was successfully cured of his addiction to toxic substances and illegal drugs.

Upon hospitalization, an intravenous antibiotic regime with piperacillin 3 × 2 g and sulbactam 3 × 1 g was initiated. Bone scans consisting of SPECT and 3-D CT of the head and neck showed extensive bony destruction of the maxilla and an accompanying osteomyelitis up to the zygomatic arches. The surgical treatment comprised a step-by-step approach. In the first step, the affected necrotic parts of the maxilla were resected to achieve clear margins. During surgery, the infraorbital and zygomatic region showed bleeding spots and vital solid bone. The diagnosis of osteonecrosis was confirmed by histopathology. In a second step two weeks later, reconstruction of the maxilla was performed using a vascularized osteomyocutaneous fibula flap from the left side (Figure 6).

To imitate the natural maxillary arch in the planning sessions, the fibula was divided into three segments and folded in the transverse plane. After inset of the osteomyocutaneous fibular flap and subcutaneous tunneling of the preauricular region, microvascular anastomoses were carried out using the left superficial temporal artery and vein as recipient vessels for the peroneal artery and the accompanying dominant vein. Surgery and postsurgical course were uneventful and a remarkably good accordance between the virtually-planned and the real outcome was recognized on postoperative CT scans. Immediately after surgery, nasal outflow ceased and facial pain was remarkably minimized.

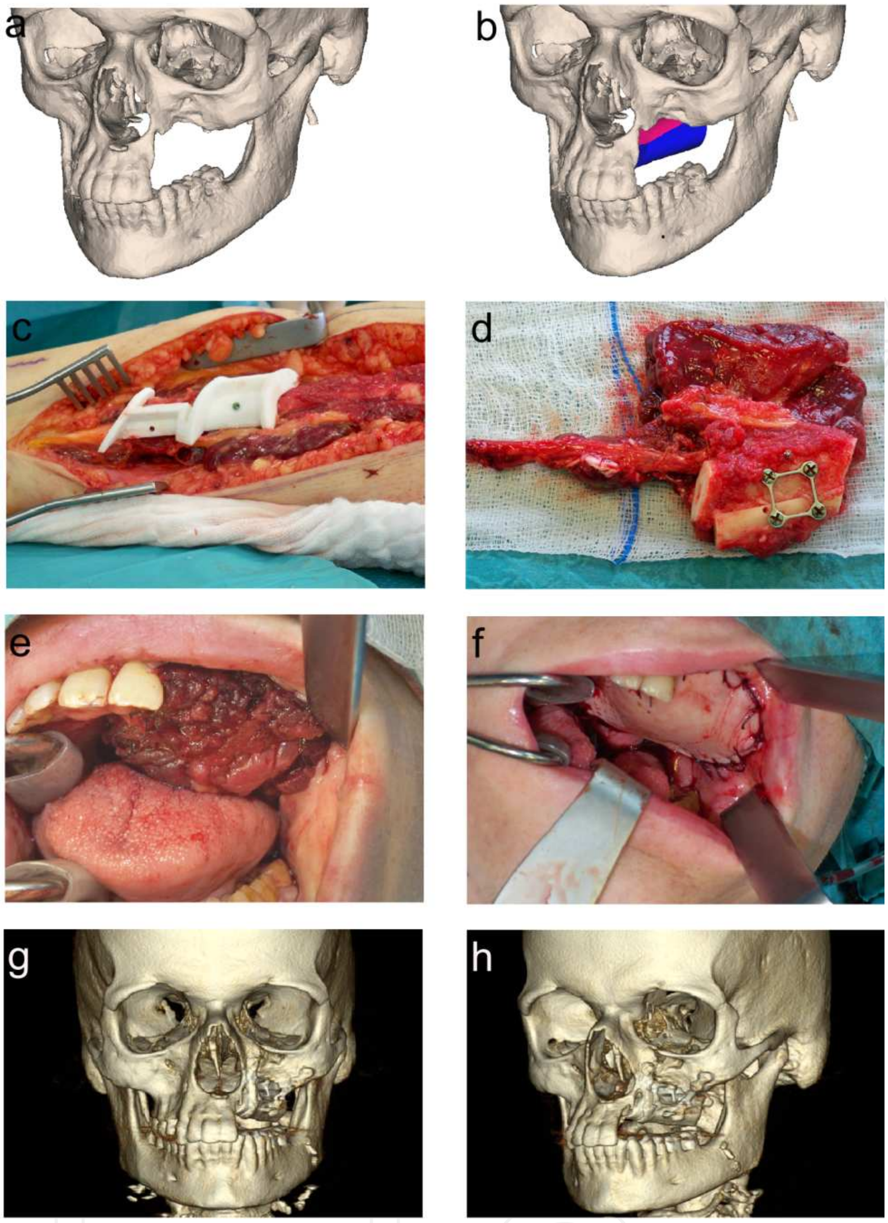

Figure 5. Case 4. (a) Initial finding of the maxillopalatine defect in the 3-D CT. (b) Virtual reconstruction with a double-barrelled fibula flap. (c) Positioning of the fibular cutting guide. (d) and (e) Prepared double-barrelled fibula flap inset into the defect area. (f) Inset of radial forearm flap for intraoral cutaneous covering. (g) and (h) Postoperative 3-D CT findings with incorporated fibula flap for osseous reconstruction.

4. Discussion

In this clinical study, we presented five different cases bearing for us some indications for the application of CAD/CAM techniques. Our report included a regional mandibular defect after tumour ablation (Case 1), extensive loss of mandibular continuity as a result of chronic osteomyelitis and ORN (Cases 2 and 3), and maxillopalatine defects (Case 4 and 5). Recent literature provides somewhat different criteria compared with ours for the application of CAD/CAM technique for osseous reconstruction [7-9]. The former comprise the requirement of

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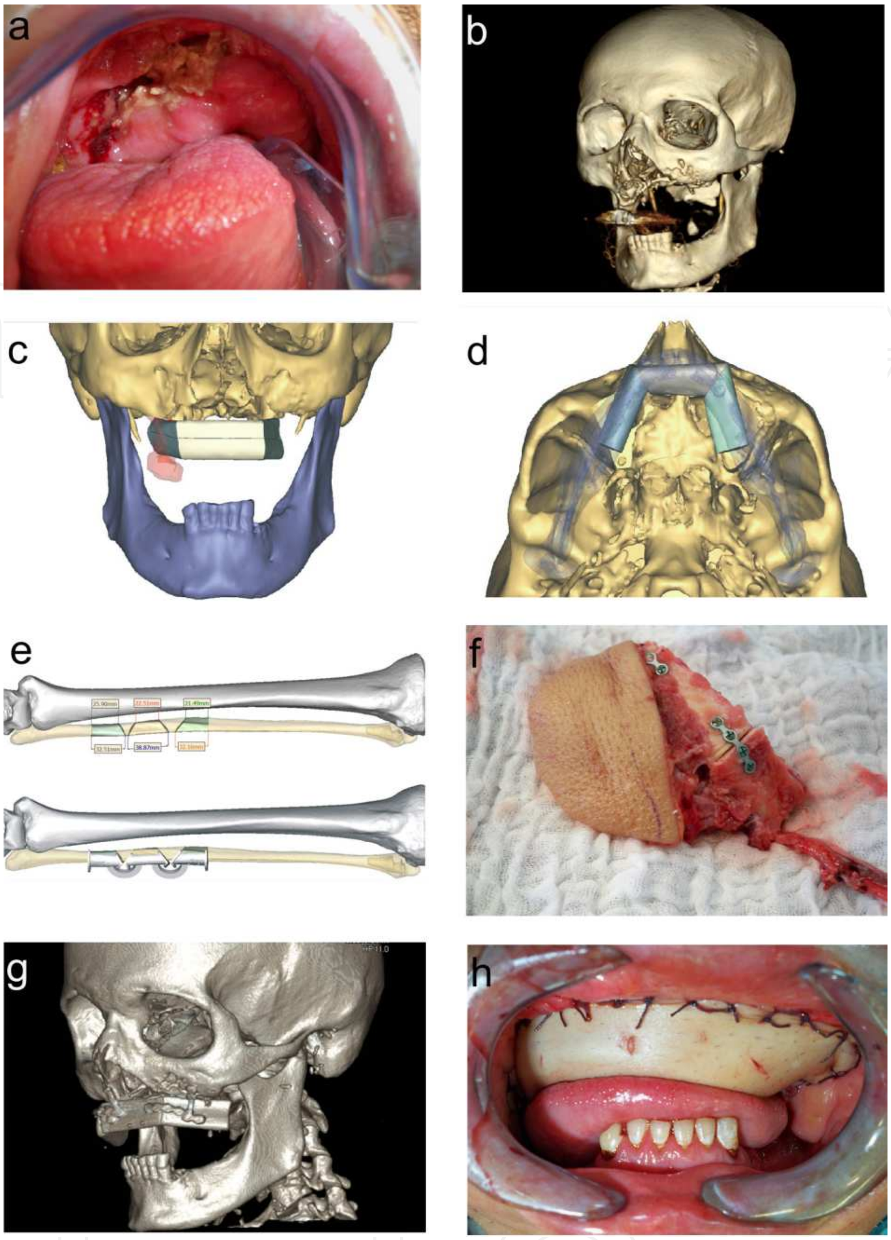

Figure 6. Case 5. (a) and (b) Extensive osteonecrosis and extensive bony destruction of the upper jaw. (c) and (d) Virtually restored native anatomy and virtually inset of fibula bone to imitate the natural maxillary arch. (e) Cutting guide for the three-segment fibula. (f) Prepared osteomyocutaneous fibula flap before inset. (g) and (h) Postoperative 3-D CT and total soft tissue covering of the former subtotal maxillary defect.

multiple osteotomies for an osseous flap, the need for multiple simultaneous free flaps, history of ORN or radiation therapy to the head and neck, and high-velocity ballistic injury with significant tissue loss. However, it is remarkable that no evidence-based studies covering these criteria are available and mostly refer to anecdotal case studies.

Keeping this in mind and following the criteria given above, only three of our presented cases should be appropriate for the CAD/CAM technique. These cases comprise osseous reconstructions obviously more complex because of having to produce segmented bone flaps (Cases

3 to 5) and employ a two-flap technique (Case 4). The two cases not meeting the criteria include the harvesting of a free iliac bone flap (Case 1) and a vascularised iliac bone flap (Case 2). Indeed, the latter cases were simpler with respect to the literature criteria and compared with Cases 3, 4 and 5. However, our experience was that the CAD/CAM technique facilitated finding and harvesting bone segments that closely duplicated the shape of the natural mandible in even less complex cases of osseous reconstruction. Without the CAD/CAM technique and cutting guides, surgery might have required further trimming and blurring of the osseous transplant without improving accuracy. At worst, it might have resulted in unnecessary scarifying of the ASIS in Case1 with further comorbidity.

However, the latter case was the only one in which compromises were necessary with respect to the accuracy of the anterolateral junction of the osseous transplant and the residual mandibular bone. Besides, the discrepancy between virtual planning and the actual finding was within the scope of a reported distance between the real and virtual osteotomies of 1.30 ± 0.59 mm [1]. Retrospectively, the source of this error is difficult to detect. Possible reasons for this inaccuracy are purely hypothetical, including movement artefacts during CT scans, metallic artefacts from filled teeth, too much play of the oscillating saw in the slots of the cutting guides, calculation errors, or simply being unfamiliar with a new method. Further studies are warranted to clarify these hypotheses.

While performing surgery with CAD/CAM devices, we experienced in Cases 2 and 3 an additional helpful aspect. After we resected the aforementioned mandibular part in Case 2, including parts of the ascending ramus, the condyle-bearing stump rotated clockwise as a result of contraction of the temporal muscle tendon. Hand-setting alone would have resulted in considerable bias when repositioning the condlye. However, by seamlessly insetting the osseous transplant, we were able to replace the condyle exactly in its initial position without further effort. Accordingly in Case 3, initial findings showed that the ascending rami were pathologically rotated medially and the condyles laterally. During virtual planning, the rotated parts were derotated and the segmented fibula flap was planned for the new position. Within the inset of the prepared fibula we achieved the planned derotation of the condyles by setting the residual mandibular stumps and fibula in a strictly axial and seamless bone-to-bone contact. Hence, the outcomes of these cases suggest that the CAD/CAM technique presents both the opportunity to accurately reconstruct osseous parts of the maxillofacial region and to solve arising or existing pathological conditions.

5. Conclusion

Our case report has fulfilled the challenge in the literature to improve upon traditional shaping methods, especially to justify the added costs [4, 10]. Furthermore, our report suggests that the possible applications of CAD/CAM techniques have not yet to be exhausted. At the current state of the art, we believe that the application of CAD/CAM techniques for osseous reconstruction in the field of maxillofacial surgery should not be restricted to obviously complex reconstructions.

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