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The application of rapid prototyping in facial surgeries: a series of case studies

Aplicação de prototipagem rápida em cirurgias de face: uma série de estudos de casos

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Abstract
Aim: *the aim of this paper is to report on the applicability of biomodels obtained from computerized tomography (CT) images through the technique of stereolithography (SLA) and three-dimensional printing (3DP), in the clinical case reports of patients who underwent surgeries involving dentoskeletal deformity, oral pathology and oral and maxillofacial trauma.* ***Methodology:*** *clinical case 01 deals with fractures in the orbital and zygomatic arch region that required reconstruction and correction of diplopia, by means of CT images, using the technique of three-dimensional printing through SLA, generating a mirrored biomodel for surgical planning and the making of customized prosthesis. In clinical case 02, by means of CT images, a biomodel utilizing the 3DP technique showed the total area invaded by invasive ameloblastoma, making it possible to plan the osteotomy with maximum preservation of the adjacent tissue and prior modeling of the plate. In clinical case 03, rapid prototyping technology (RP) was used to make customized prosthesis for temporomandibular joint, with the goal of correcting a serious idiopathic pathology provoking the resorption of the right and left condyles.* ***Discussion:*** *complex cases require the team to have recourse to technology for the implementation of the procedures, in order to offer excellent quality treatment to the patient, in addition to facilitating surgical planning and permitting the construction of customized prostheses.* ***Conclusion:*** *the rapid prototyping for the acquisition of biomodels is an important auxiliary tool for the surgical team.*
Keywords: *Imaging. Three-dimensional. Tomography.*

Resumo
Objetivo: o objetivo deste estudo foi informar sobre a aplicabilidade de biomodelos obtidos a partir de imagens de tomografia computadorizada (TC) através da técnica de estereolitografia (SLA) e impressão tridimensional (3DP), nos casos clínicos de pacientes submetidos a cirurgias envolvendo deformidade dentoesquelética, patologia oral e trauma oral e maxilofacial. **Metodologia:** o caso clínico 01 trata de fraturas na região do arco orbital e zigomático que requerem reconstrução e correção da diplopia, por meio de imagens de TC, usando a técnica de impressão tridimensional através de SLA, gerando um biomodelo espelhado para planejamento cirúrgico e fabricação de próteses personalizadas. No caso clínico 02, por meio de imagens TC, um biomodelo utilizando a técnica 3DP mostrou a área total invadida pelo ameloblastoma, possibilitando o planejamento da osteotomia com preservação máxima do tecido adjacente e modelagem prévia da placa. No caso clínico 03, a tecnologia de prototipagem rápida (RP) foi utilizada para fabricar próteses personalizadas para a articulação temporomandibular, com o objetivo de corrigir uma séria patologia idiopática que provocou a reabsorção dos côndilos direito e esquerdo. **Discussão**: casos complexos exigem que a equipe recorra à tecnologia para realização dos procedimentos, a fim de oferecer um tratamento de excelência e qualidade ao paciente, além de facilitar o planejamento cirúrgico e permitir a construção de próteses personalizadas. **Conclusão:** a prototipagem rápida para aquisição de biomodelos é uma importante ferramenta auxiliar para equipe cirúrgica.
Palavras-chave: Imagem Tridimensional. Tomografia

INTRODUCTION

Rapid prototyping is a technique for manufacturing parts using a model generated by a CAD (computer aided design) system, in which they are sectioned into 2D (two-dimensional) profiles that are built-up layer by layer.[1] Various techniques are presently used and available for application in diverse areas, including: stereolithography (SLA), direct metal laser sintering of metal (DMLS), selective laser melting (SLM), fused deposition modeling (FDM), 3D printing (3DP) and electron beam melting (EBM).[1, 2]

The process of Rapid Prototyping (RP) was developed primarily for use in mechanical engineering, but its medical applications are becoming increasingly common.[3] The medical models produced through RP are being applied in a number of cases of craniomaxillofacial surgery using the

Correspondente/Corresponding: * Pedro Paulo Oliveira Carneiro – Centro Universitário UNINASSAU, Departamento de Biomedicina. – End: Rua dos Maçons, 364 – Pituba, Salvador-BA. CEP:41810-205. Tel: (71) 99191-6116 – E-mail: carneiro.ppoc@gmail.com

technique of sterolithography. RP is much used in highly complicated surgeries by means of virtual simulation, allowing prior planning of the surgical procedure.[4]

Biomodels are biomedical prototypes developed on the basis of images captured through computerized tomography (CT), nuclear magnetic resonance (NMR) and ultrasound (USG). These images are processed in a specific system for transposition into 3D (three dimensions) or 2D[5], in other words, where there is data describing an arbitrary three-dimensional form (3D), there is the potential to produce a physical object that can be executed by means of RP. With the evolution of medical imaging techniques, it is possible to obtain detailed analyses of the patient's anatomic structure and functioning, being that each of these techniques uses different physical principles, in such a manner as to generate a set of transversal images of the human body, DICOM (Digital Imaging Communications in Medicine). The latter is characterized as a set of norms for treatment, storage and transmission of medical information in an electronic format, between different brands of equipment that may or not be compatible, and between imaging equipment and computers.[6, 7]

The protoype is a product that is manufactured unitarily, following design specifications, with the purpose of serving as a test. It can be said that the prototype is a virtual or real experiment that simulates a real system. In the medical and odontological areas, biomodels are developed based on the concept of industrial rapid prototyping.[8]

Rapid prototyping possesses many applications in Dentistry in the specialties of orthodontics, implantodontics, and in oral and maxillofacial surgery and traumatology; according to Meurer, Mazzonetto and collaborators, the acquisition of biomodels permits a more precise diagnosis in reconstructive surgeries, the treatment of traumatic lesions, and osteogenic and temporomandibular joint distractions.[8]

Information technology is a great ally in the confection of biomodels, through software programs developed for image capturing and editing. Technological advances contribute every year to the manufacture of biomodels, facilitating the process of image data transmission and the subsequent printing of the biomodel. That which previously required a week to make ready, due to the nature of the process in conjunction with the cost of the biomodel, can presently, after the capturing and editing of the images, be ready in up to twenty-four hours for use in surgical planning. Limitation is associated with the complexity of the case to be addressed.[8]

It is recognized at present that costs for the treatment of patients bearing facial deformities are exorbitant for the Brazilian Single [Public] Health System (SUS). These costs arise from various factors: surgical complications, length of hospitalization, supplies, work hours of the interdisciplinary teams involved, auxilary personnel and medicines.[9, 10]

The objective of this study was to report on the applicability of biomodels obtained from computerized tomography images via the technique of stereolithography (SLA) and three-dimensional printing (3DP), through clinical case reports of patients submitted to surgical procedures involving dentoskeletal deformity, oral pathology and oral and maxillofacial traumatology; the three cases reported upon present satisfactory results in their respective postoperative conditions.

METODOLOGY

The study was carried out with three clinical cases of facial pathology, referred-to in the text as clinical case 01, clinical case 02 and clinical case 03. All participants in the study signed the free and informed consent form. Three distinct pathologies are involved: clinical case 01 concerns multiple fractures of the face in the orbital region; clinical case 02 deals with a benign odontogenic neoplasm of epithelial origin (ameloblastoma) of the mandible, and clinical case 03 concerns an idiopathic condylar resorption. All of them required RP biomodels made with a 3D printer for the effectuation of the model surgery. The materials used in the three cases were two techniques of 3D printing, being that in clinical cases 01 and 03 the biomodel was printed using the SLA technique. In clinical case 02, three-dimensional printing (3DP) was used.

It was necessary to follow a series of stages in order to create the biomodels: first the patients were submitted to CT and the images acquired were sent to the open software program (InVesalius®)[11] for three-dimensional reconstruction of anatomical structures, in order for the images to be adequately processed. In clinical case 01, it was not simply a question of constructing the biomodel, but also of constructing customized prostheses of the orbit. In this case, a biomodel was manufactured through the SLA technique, using the tool that creates a mirror, that is, a copy of the side that did not undergo trauma; thus, the biomodel was printed as if the patient's face had not undergone any trauma. The next step was to recreate the orbit walls and floors, manually, in wax, making them as thin as the patient's natural bones. Finally, the creation of the final prosthesis was planned with the InVesalius® software in 3D for the printing of the Poliquil® vegetable polymer prosthesis.

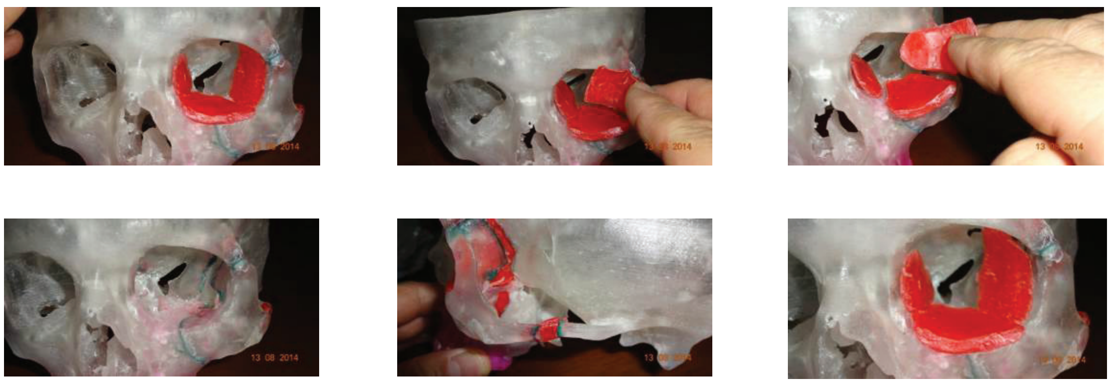
In clinical case 02, after construction of the biomodel, only the modeling of the plate was done. The biomodel, in this case, was printed with three-dimensional printing (3DP). This technique printed it by the affixing of layers through an agglutination of plaster and starch, and built it by means of successive layers of powder pulverized in an adhesion solution, selectively agglutinating the necessary granules. In clinical case 03, the biomodel was produced in order to construct TMJ (temporomandibular joint) prostheses. For this case, the best option for printing the biomodel was also the SLA technique, which permitted the making of cuts in the biomodel in order to apply the prototype of the TMJ prostheses, promoting greater security and precision in the planning and production of the definitive prosthesis.

CASE REPORTS

Clinical Case 01: Multiple Fractures in the Orbital Region (Orbital Implant)

Patient 23 years old, bearing alterations of the orbit and zygomatic arch provoked by a motorcycle accident around a year ago. The resultant fractures led to dipoplia and facial assymetry. The patient underwent a cranial CT for appropriate surgical planning. The surgical team decided to create a biomodel using rapid prototyping with the technique of stereolithography (SLA). Three wax pieces were molded manually (in red, corresponding to the desired prostheses as shown in Figure 1).

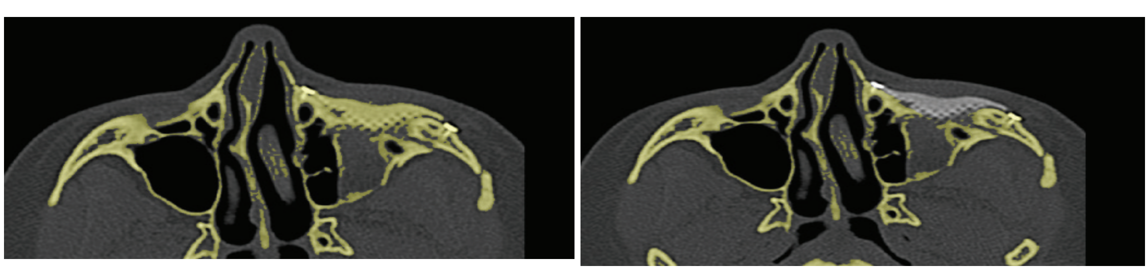
Figure 1 – *Mirrored biomodel made with a 3D printer by RP using the SLA technique (different angulations).*



Source: Own authorship

In order to generate the prostheses models, it was necessary to computationally reproduce the manual work in such a way as to generate a new internal model of the orbit, to be used as a base for the design of the prostheses. This task was extremely complex and required a great amount of time, as the difference between the patient's tissue and the already-implanted prosthesis was not clear in the tomography. In order for the prosthesis to be reproduced identically with the patient's anatomical format, it was necessary to print a mirrored biomodel. CT images were selected in a slice that showed the fractures and made it possible to effect the necessary prior corrections before sending them for the second stage of correction (Figure 2). Next, the selected images were corrected in the CAD 3D program, which allowed the reproduction of the CT image as a 3D image with the entire area to be corrected, generating a copy identical with the opposite side, that hadn't suffered any trauma. Through this technique, it was possible to reliably print the prosthesis that was applied to the patient's fractured side (Figure 3).

Figure 2 – *CT image (axial slice) and detailing of the fracture for printing of the mirrored biomodel*



Source: Own authorship

Figure 3 – *Image of the frontal cranium with fracture of the zygomatic arch and mirrored image.*

From there, virtual models were generated using the open software program InVesalius® for three-dimensional reconstruction of anatomical structures, and after this process, the computational model of the prosthesis was arrived at. This was sent to the rapid prototyping machine in order to generate the physical model used as a pattern for molding the final material of the prosthesis. Fig 4 illustrates the result of this process.

Source: Own authorship

Figure 4 – *Virtual reconstruction of the traumatized area (3D) and simulation of the prostheses.*

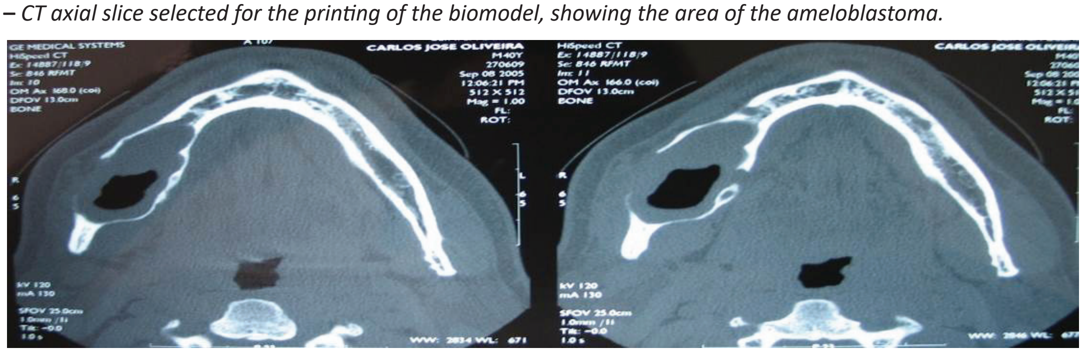
Source: Own authorship

The prostheses were created using the vegetable polymer Poliquil®. The patient made good postoperatory progress, and was discharged forty-eight hours after the procedure. Both the dipoplia and the facial assymetry were satisfactorily corrected and the patient is presently being seen as an outpatient.

Clinical Case 02: Mandibular Reconstruction

Patient 40 years old, bearer of ameloblastoma on the right of the mandible. The biomodel was made with the objective of planning the exeresis of the tumor and immediate reconstruction of the area. The acquisition of images followed the protocol established in axial slices (Figure 5), based on the CT-generated images and with the support of open software InVesalius® for three-dimensional reconstruction of anatomical structures.

Figure 5 – *CT axial slice selected for the printing of the biomodel, showing the area of the ameloblastoma.*



Source: Own authorship

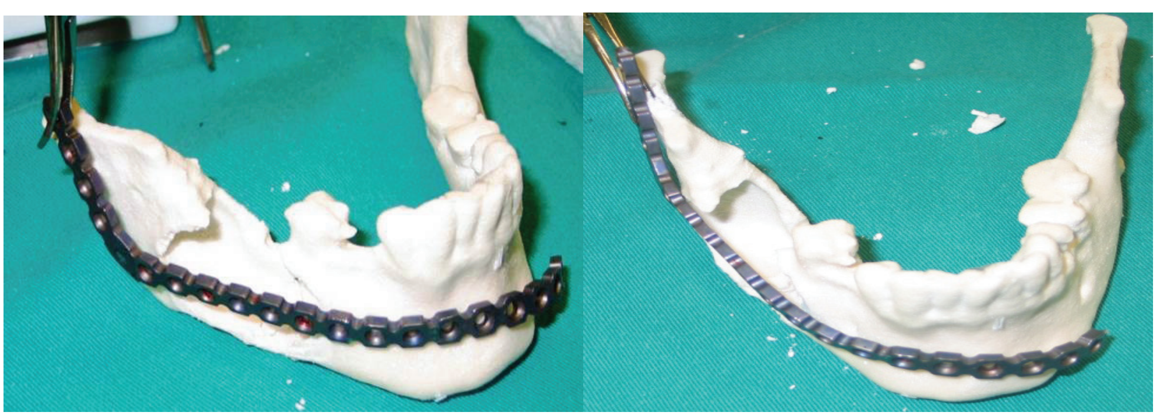
For 3D printing, the biomodel was created with all specifications, respecting the patient's original anatomy, measuring the size of the tumor and using three-dimensional printing technique (3DP) (Figure 6).

Figure 6 – *Biomodel generated using three-dimensional printing technique (3DP), seen from different angles.*

Source: Own authorship

With the biomodel in hand, the surgical team was able to carry out the surgical planning and choose the plate to be applied, as well as assess the edges to be osteotomized. For this patient, the resection of the edge of the mandible was planned, preserving the maximum amount of remaining bone for the fixation of the plate in the transversal dimension of the mandible and occlusion. A reconstruction plate of 2.4mm, manufactured by Neoortho®, was modeled following the anatomical outline of the mandible, adjusting the height and exact position (Figure 7). The team carried out the osteotomy and abrasion of the remaining bone, fixating the aforementioned plate on the entire segment.

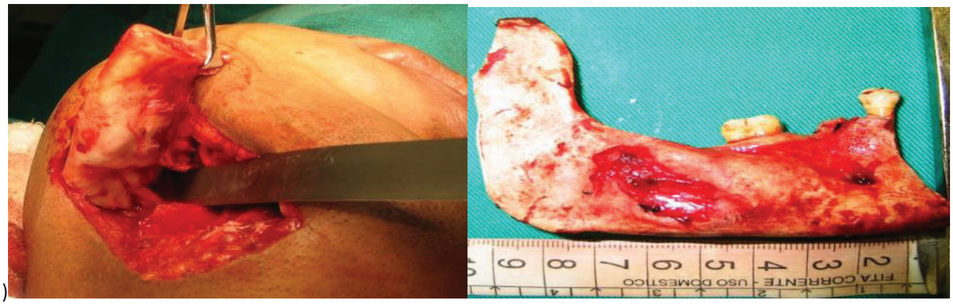
Figure 7 – *Modeling of the Neoortho® plate on the biomodel and marking of the osteotomy.*



Source: Own authorship

The patient was then submitted to the surgical process in accordance with the preliminary planning. With the help of the biomodel, the surgical team carried out the osteotomy, preserving the remaining bone for the fixation of the plate, seen in Figures 8 A and B, repeating the steps for the fixation of the previously modeled plate on the patient. The resemblance between the surgery effected on the model and in the perioperatory period can be observed in Figures 9 A and B.

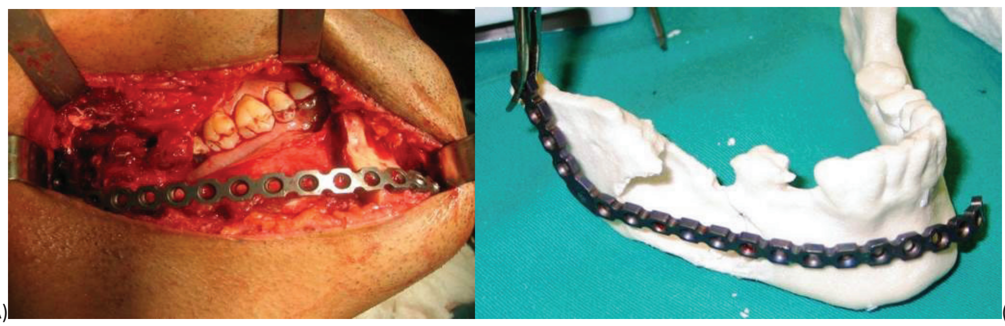
Figure 8 – *Osteotomy of the mandible and exeresis of the tumor*

(A)  (B)

(A) Perioperatory. (B) Specimen.

Source: Own authorship

Figure 9 – *Similarity between the surgery effected on the model and in the perioperatory phase.*

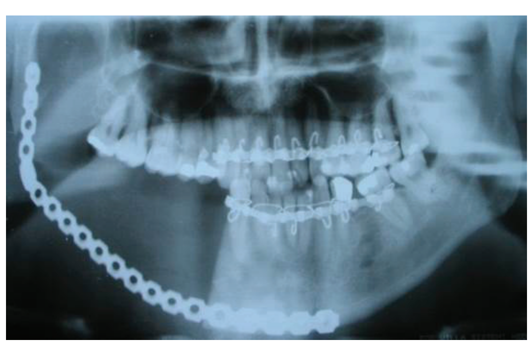
(A)  (B)

(A) Fixation of the plate in the perioperatory stage and (B) modeling of the plate during the planning stage.

Source: Own authorship

The panoramic radiograph for postoperatory monitoring shows the osteotomy as well as the positioning of the plate (Figure 10). A maxillomandibular block (MMB) was carried out with an Erich arch bar to limit the plate's movements in the postoperatory phase. The goal of performing the exeresis of the tumor with preservation of the remaining mandibular bone and immediate reconstruction was reached, demonstrating that the technique was satisfactory.

Figura 10 – *Postoperatory panoramic control x-ray.*

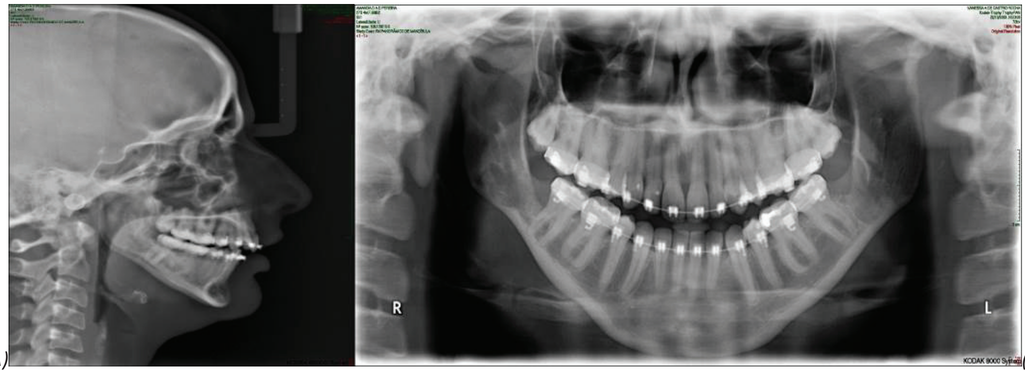


Source: Own authorship

Clinical Case 03: Condylar Resorption

Patient 26 years old, sought out the Oral and Maxillofacial Surgery office, complaining of intense pains, limitation of the oral opening and serious respiratory alteration, with a diagnosis of severe arthritis and a surgical referral for placement of prostheses of the temporomandibular joint (TMJ). In order to conclude the diagnosis a facial analysis was done, as well as an intra-buccal clinical examination, and analysis of the panoramic and profile radiograph, explained in Figures 11 A and B.

Figura 11 – *Diagnostic image exam*



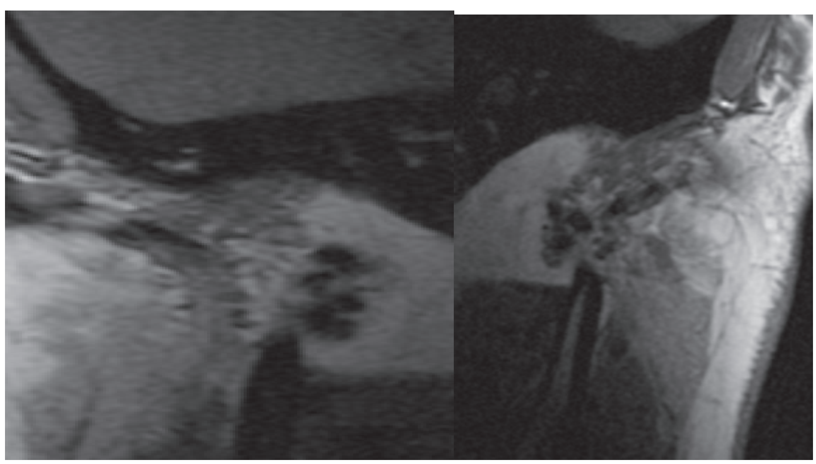
(A) *(B)*

(A) Teleradiography of the profile and (B) panoramic x-ray of the face.

Source: Own authorship

Given the radiographic and tomographic findings, the surgeon responsible for the case decided on the placement of Concepts® customized TMJ prostheses, combined with orthognathic surgery. NMR images are seen in Figure 12.

Figura 12 – *NMR of the TMJs: severe hypoplasia, erosion and resorption in both condyles.*



Source: Own authorship

In order to carry out the procedure, it was necessary to acquire a biomodel through rapid protoyping made in 3D via the SLA technique (in order to effect the customization of the prostheses). In addition, digital surgical planning was done using the cone beam tomography images of the patient through Dophin Imaging® 3D software.

In order to make the prostheses it was necessary to follow the protocol developed by the manufacturer, that starts with filling out a form called "order form" which contains all the information needed in order to begin manufacturing. Next, the CT images were sent out in order to acquire the biomodel to be printed in 3D (with the SLA technique). With the biomodel in hand, a prototype of the TMJ prosthesis was made, with the ideal size, angulations, sizes of fixation screws and mandibular movements for correction of the pathology.

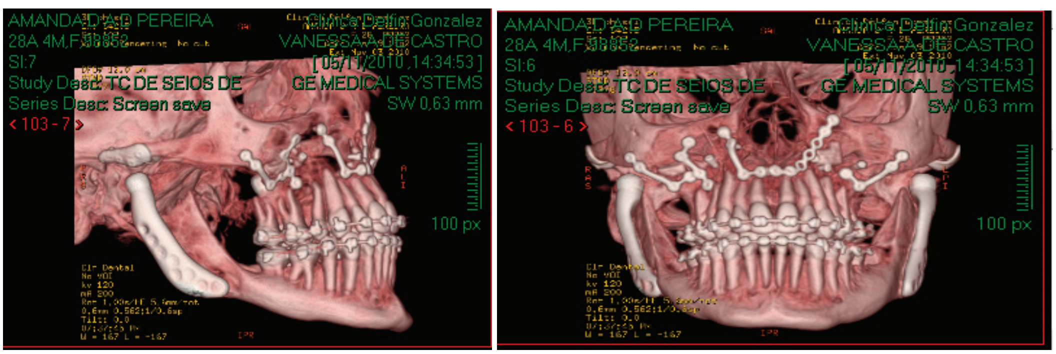
After the surgeon's approval was obtained, and in accordance with the virtual surgical planning, the definitive prostheses were made up, like the one shown in Figure 13, and applied to the biomodel before finalization.

Figura 13 – *Biomodel with a prototype of the prosthesis for assessment and finalization of planning.*

Source: Own authorship

In the postoperatory images, the perfect occlusion and facial symmetry are remarkable (Figure 14). In addition to receiving the TMJ prostheses, the patient was submitted to orthognathic surgery, as previously mentioned. With virtual planning and acquisition of the biomodel, it was possible to plan the mandibular advancement and segmentation of the maxilla, which was fixated with Osteomed Corp® titanium plates.

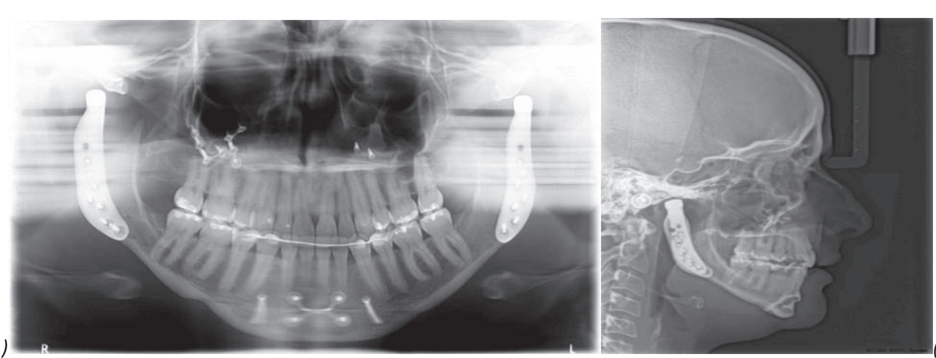
Figura 14 – *Postoperatory CT images: positioning of the Concepts® prosthesis and the Osteomed Corp® fixation plates.*



Source: Own authorship

The result was satisfactory, as shown in Figures 15 A and B. The patient continues to be followed as an outpatient, and after six years of follow-up possesses stable occlusion, complete absence of pain and a well positioned prosthesis, according to the radiographic image.

Figura 15 – *Postoperatory images six years after the surgery*

(A)

(B)

(A) Panoramic radiography (B) Profile teleradiography

Source: Own authorship

RESULTS AND DISCUSSION

Craniofacial abnormalities (CFA) constitute a highly diverse and complex group that, as a whole, affect a significant proportion of the people in the world.[12] The rehabilitation of individuals with craniofacial deformities generated by trauma, congenital malformations *or tumors, is challenging and complex. The majority of resources and treatment options have brought progress in terms of patient survival rate, making rehabilitation more necessary and urgent.[13]*

Several surgeons have had recourse to rapid prototyping with the goal of obtaining biomodels that help in the solving of complex cases involving craniofacial anomalies.[10, 13-16]

Complex cases require the team to have recourse to technology for the implementation of the procedures, in order to offer excellent quality treatment to the patient, in addition to facilitating surgical planning and permitting the construction of customized prostheses.[17]

Having access to the technology of software programs that are able to reproduce images in 3D, coupled with the planning for virtual reconstruction of the face, is extremely important for the final result.[16] Although the initial cost is high, the benefits of such a technique are remarkable, and include prior planning; anticipation of difficulties and solutions for same; optimized perioperatory approach; reduction of the length of surgery and, consequently, reduced exposure time of the patient to the risk of infection.

Software programs like Dolphin Imaging® and InVesalius® figure as extremely important tools in the surgical planning process and in the production of customized biomodels and prostheses. They make it possible to assess the entire area to be worked on, and to reproduce faults and correct them virtually so that the biomodels can be printed with a 3D printer, in conformity with the patient's anatomy. They also make it possible, after image correction, to manufacture prostheses that can be used for tests.

The prostheses of case 01 were made with the vegetable polymer Poliquil®, and though the whole process described involves activities that demand quite a lot of computational time and the creation of models and adjustments, the principal result was the acquisition of prostheses that were completely personalized for the patient's anatomy/pathology, which would not have been possible if using prostheses with a standard geometry, such as are encountered for this type of application. As far as its properties are concerned, this polymer is biocompatible due to its molecular structure, yet offers resistance, flexibility and stability. Poliquil® can exactly reproduce the need for correction of the damaged part of the anatomy; in other words, a customized prosthesis is made specifically for each case. Thus, the area where the prosthesis is to be applied does not need to be manipulated in an exaggerated fashion, which reduces surgery time and the patient's exposure to risk of infections.

For the surgical planning of clinical case 01, it was seen that a biomodel would need to be made. The latter served as a physical guide to the multiple fractures in the orbital region and provided direction as to how to correct them in the manner that would offer the best possible result. In addition, based on the creation of the biomodel, it was possible to make customized prostheses with specific sizes and measurements, which consequently made it practicable to correct the dipoplia (an important complication that could only be surgically corrected), as well as making it possible to correct the facial assymetry that had caused the patient psychological trauma.

In clinical case 02, the patient was diagnosed with ameloblastoma, a slowly growing odontogenic tumor that is generally benign. [18, 19] The majority of ameloblastomas affect the mandible, being primarily observed in the rami and body[18]. The predilection peaks according to age group are between 20 and 30 years of age, consistent with the age of the patient in this case.[19]

They are also characterized as locally invasive tumors, and are expansive, with the ability to perforate the cortical bone and invade adjacent soft tissues; thus, with the aid of a biomodel, the visualization of the extension of the tumor is of the highest importance in order to accomplish its complete exeresis.[19]

The behavior of the ameloblastoma tends to be quite aggressive in its relapses, with greater destructive potential than the original lesion.[19] Surgical planning with the biomodel avoids the incomplete removal of any tissue, besides which it is possible to immediately plan mandibular reconstruction. In a complex surgical procedure such as this, the biomodel gave the team a sense of security as they carried out the osteotomies in such a manner as to extirpate the entire tumor. It also permitted prior modeling of the plate, which led to a reduction in length of surgery and hospital costs. In the postoperatory radiographic images, one can observe the satisfactory result of the osteotomy and of the application of the plate according to the model surgery. There was no need to adjust or remodel the plate at the time of reconstruction nor was there any bone abrasion aside from that which had been planned on.

In clinical case 03, the radiological and tomographical results determine the diagnosis of severe condylar resorption in the right and left condyles, and the condition of arthritis diagnosed by the rheumatologist. The literature relates that idiopathic condylar resorption, also known as idiopathic condylitis, condylar atrophy and progressive condylar resorption, is a well-documented though poorly-understood condition.[20]

For the correction of the pathology, total reconstruction of the TMJs is indicated, with the placement of customized prostheses. Total prosthetic reconstruction of the TMJs is recommended for purposes of improving pain, function, diet, maximum incisal opening and quality of life. Thus, the reconstruction of this structure with these devices guarantees safe, effective and reliable prosthetic substitution for a pathological or seriously compromised TMJ, as long as diagnostic and surgical criteria are well assessed. [21]

The prostheses of case 03 were customized according to CT images and the biomodel printed with a 3D printer. The latter were previously applied for purposes of validation in the model surgery, with the carrying out of the definitive surgical procedure being dependent on this validation. The postoperatory radiological and tomograph-

ical images, as well as those from the six-year follow-up referring to the case, confirm the effective results.

In this case, what is important is generating solid models of the internal part, reproducing the manual work indicated by the surgeon, while respecting the conditions of symmetry of the patient's face. Additional precautions must be taken not to obtain very fine wall prostheses, which would render their manufacture impossible and make them extremely fragile. It is an interactive task: the computational part is effected, the result verified, and if it is not approved, the work is repeated with due corrections.

CONCLUSION

Biomodels, made with the technique of Rapid Prototyping, offered benefits to the surgical team in the process of planning the entire surgical act, that included osteotomies, assessment of prosthesis positioning and the sizes of the plates to be fixated; thus, length of surgery was optimized, morbidity risks were appreciably reduced and the team was able to work with an increased sense of security.

It is certain that rapid prototyping is not part of the routine of oral and maxillofacial reference centers on account of the cost of acquiring biomodels, in addition to the necessity of integrating other professionals with the team (information technology professionals, 3D printing laboratories, among others). Nevertheless, it is believed that with the spread of technology and reduction of costs in the near future, reference centers will be able to have access to this very important resource.

Based on the clinical cases reported here and on others found in the literature, we conclude that Rapid Prototyping for the acquisition of biomodels is an auxiliary tool of the utmost importance for the surgical team's planning. With the aid of this resource, it is possible to improve surgical planning and execution, principally in complex cases of facial deformity. The benefits are well proven on the basis of observation of the results of various cases in which this techonology was utilized.

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