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PATIENT SPECIFIC IMPLANT DESIGN AND PRODUCTION FOR CLOSURE OF SKULL DEFECTS

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Abstract: In order to provide a function on the body, implant as defined organic and inorganic substance that is placed in an appropriate place, means that the type of material to be placed within the body in medicine. Considering the concept called as a prosthesis that completing artificially any part of the body that is lost and helping heal, for the purposes mentioned, artificial prosthesis structures such as joint prosthesis used in orthopedic surgery, placed in tissue, skull implant prosthesis that are used in brain surgery. The biggest advantages of implant prosthesis compared with other conservative treatment methods are much more robust, comfortable, and reliable. In many countries, due to traffic accidents and terror attacks, brain injuries and damages are frequently observed. Because of that sort of situation, in the process of treatment, such as brain trauma, skull implants are needed. All implants that are used for surgical purposes must also be sterile. Depending on technological developments, according to the needs, there are various implant manufacturing machines, software programs and hardware. In this study, it is intended to design and develop Cranial Implant Prosthesis to be used for closure of skull defects and implementation to the selected patients. For this purpose, CT images of patients are used. MIMICS software and surgical simulation tools are utilized for producing 3D model of the skull. Finite element analysis of titanium has been done by Patran software. The maximum displacement of the implant, maximum stress parameters are measured with the statistical data and supported with related figures. Various analyses have been done during the implementation of skull implant and the results are evaluated in details.

Keywords: Skull implant, craniofacial implant

Introduction

Traumatic brain injury results from an external force to the brain due to road traffic accidents, falls, natural disasters and terror attacks are associated with high mortality and severe disability rates throughout the world (Peeters et al., 2015). The severity of the injury determines the prognosis. Even minor head injuries can be related with psychological or learning disabilities. On the other hand, critical head injuries can result in death, permanent coma, serious consequences or rarely, full recovery. Cranial fractures are generally diagnosed with computed tomography (CT) scanning. CT scan is especially useful in the evaluation of acute head injuries. The details on a CT scan are excellent, and moreover very little spots of blood may be seen. Therefore, in the process of treatment of brain trauma, skull implants are needed. When cranial bone is lost, subsequent reconstruction of the skull defect is necessary to protect underlying brain tissue and improve cosmesis (Scholz, 2007).

Medical implants are devices that are set inside or on the surface of the human body. The aim of a prosthetic implant material is to replace a missing part or a function of the body. The characteristic features needed for the implant material are to be safe, reliable, economical, and physiologically acceptable. Depending on technological developments, according to the needs, there are various implant manufacturing machines, software and hardware.

Three-Dimensional (3D) CAD/CAM Implants

Rapid developments in medical imaging and advances in computer-aided design/manufacturing (CAD/ CAM) improved the quality of implants, resulted in improved aesthetic outcome, minimized operating time, blood loss and risk of infection (Chen et al., 2015). Patient-specific implants, of any size with an accurate fit, were produced by using these new technological devices. Recent studies showed that reconstruction of large skull bone defects with patient-specific implants contributed to pain and headache reduction frequently seen following craniectomy and increased postoperative quality of life (Wehmoller et al., 2004; Eufinger et al., 2005; Cabraja et al., 2009).

CAD creates 3D reconstructions of bony contours, while these geometric models contribute for the direct CAM of implants in computerized numerically controlled milling machines without a need for indirect manual modeling on full-size models. Resection and reconstruction are performed in a single-step surgical procedure (Eufinger, 1998).

Cranial defect reconstruction being founded on digital and rapid prototyping technology is appreciated by surgeons for its personalization, effectiveness and accuracy. The primary advantage of the computer-aided techniques is a better cosmetic result. Additionally having an exact fitting plate also executes insertion easier and long-term complications of scalp pressure should be less frequent. The processing of individual CT data with CAD/CAM techniques is a relatively new technology capable of producing custom-made implants for the reconstruction of large skull defects in the field of cranial surgery. The goal of three-dimensional (3D) CAD/CAM implants is to obtain a physical model with the same geometric characteristics as the virtual one, so that it can be used in the repair of the defect (van der Meer, 2013). The presented digital workflow to create individual cranial implants is fast and practical. Because of the complexity of the topic, a good collaboration between engineers, radiologists and surgeons is needed to achieve good segmentation, resolution and finally an accurate 3D model. The creation of the cranial implant with optimal size, shape and mechanical properties prior to the surgical procedure reduces the operation time and complexity, due to the preoperative planning using correct geometrical and anatomical details and improves surgical accuracy (Jardini et al., 2014).

Although there are lots of benefits of prefabricated, patient-specific implants, there are specific disadvantages that restricts their widespread application. The high costs of the custom prefabricated implants usually limit its implementation to only the most difficult and complex defects. Additionally, prefabricated implants are made to reconstruct a specific defect and are, therefore, confined to patients with fixed cranial defects with precise size and geometry, known preoperatively. In the need of intraoperative modification of the size, shape or bony margin of the defect, implant becomes virtually useless. The clinical meaning is, this can be seen in all situations in which a craniectomy is carried out to remove bony tumors of the skull, osteoradionecrotic bone or osteomyelitis bone (van Putten & Yamada S, 1992).

Cranioplasty is described as the surgical repair, replacement and restoration of a cranial defect, hence realizing morphological and functional rehabilitation of the cranial vault. Along with its cosmetic and protective roles, cranioplasty has also been shown to play a functional and therapeutic role as it assists to reverse the characteristics of a condition called the motor trephine syndrome (MTS), in which neurosensory and motor deficits due to derangements in cerebral hemodynamics, cerebrospinal fluid hydrodynamics and shrinkage and relocation of intracranial structures, secondary to large skull defects are present (Alibhai, et al, 2013).

Titanium Cranioplasty

Numerous techniques and materials have been evaluated in the reconstruction of the cranial defects, such as autografts to xenografts and bone substitutes, including calcium phosphate, polymethyl methacrylate, hydroxyapatite, porous polyethylene, and titanium. All implants that are used for surgical purposes must be sterile (Arun Kumar et al., 2014). An ideal cranioplasty material must fit the cranial defect and get complete closure, be radiolucent, non-magnetic, tissue acceptable, durable, resistant to infections, strong to biomechanical processes, easy to shape, not dilate with heat and not to be expensive. While the Incas used gold and silver materials in cranioplasty, in modern ages the first metal used in cranioplasty is aluminum. Unfortunately, many infectious complications occurred in patients with aluminum implants. Additionally, many patients suffered from epilepsy following the implantation of aluminum. So, aluminum material for cranioplasty is no longer used. Moreover, methylmethacrylate (MMA) has been demonstrated to have better compression and stress resistance in comparison with hydroxyapatite (Marchac, 2008). Poly-methylmethacrylate (PMMA) is also used as an implant material for cranioplasty. It is a polymerized ester of acrylic acid with strength like bone. However it has disadvantages as its ability to stimulate osteolysis and impair the body natural defense systems (Shan, 2014).

The procedures for the usage of these materials depend on the medical centers, as some surgeons prefer to shape the implant intraoperatively, and others select to create custom-made plates preoperatively using CT or stereolithography data. As each of the implant materials has its advantages and disadvantages, the preference of the material is based on them. Studies have shown that synthetic materials for cranial bone defect reconstruction are found to exhibit more promising outcomes compared with autograft (Piitulainen et al., 2015). Nowadays, titanium is considered as the most biocompatible alloplastic material and is recommended as the method of choice for secondary cranioplasty (Cabraja et al., 2009). It is resistant to corrosion, adaptive to bony surfaces, can be easily shaped to fit the specific contour of any given defect and has a high strength/weight ratio, low density and non-magnetic properties and an ability to withstand high temperatures. The low density of titanium offers perfect mechanical properties for the stabilization of the graft beneath the membrane. Additionally, its elasticity and stability prevent mucosal compression and graft displacement leading to good cosmetic and functional results (Spetzger, 2010).

The components of titanium alloy are shown in Table 1.

Table 1. Components of titanium alloy (Facchini et al., 2009)

Component	%
Titanium (Ti)	Balance
Aluminum (Al)	5,5-6,75
Vanadium (V)	3,5-4,5
Iron (Fe)	<0,3
Carbon (C)	<0,1
Oxygen (O)	<0,2
Nitrogen (N)	<0,05
Hydrogen (H)	<0,01

The use of titanium patient-specific implants is well defined and the complication rates and surgical removal rates are reported to be between 4.1% to 29% and 0% to 15.9%, respectively (Kung et al., 2012; Williams et al., 2016). Cabraja et al. (2009) carried out a long-term follow-up research of 26 patients after installation of CAD/CAM titanium for cranioplasty. They reported that none of the plates had to be removed, and nearly 90% of the patients are satisfied with an overall outcome.

Many methods for preparing custom titanium cranioplasty plates have been described. These techniques generally start by preparing a model of the defect from CT data and designing a surface to mimic the missing cranial segment. The model of the defect can be virtual or, according to the reconstruction surgical team, a physical three-dimensional (3D) model of the defect, can be built using rapid-prototyping techniques. Once the surface is ready, then an implant is designed from this surface to repair the defect (Petzold, 1999).

Preference of Ti6Al4V Biocomposite

Cranioplasty is known as one of the oldest surgical interventions. There is an archaeological evidence that ancient Incans used gold to reconstruct trephination holes around 3000 BC. The earliest written document of cranioplasty is from 1505 when Ibrahim bin Abdullah, an Ottoman-era military surgeon, recommended the use of a cranial xenograft from a goat or dog. Afterwards, the Italian Fallopius described cranioplasty with a gold plate in 1561. During this long period, various techniques have been used to repair these deformities using autografts, allografts and biomaterials. Unfortunately, as a result still there is no ideal technique as each method has its limitations (Black, 1978). Similarly, lead is utilized as a cranioplasty material at the beginning of 20th century. Nevertheless, its usage is stopped due to its toxicity and related deaths. On the other hand, platinum showed good biocompatibility. But its usage is limited due to its expensive costs (Sanan, 1997). Vitallium includes cobalt, molybdenum, and chrome. In animal experiments, it is shown that it gives less tissue reaction in comparison with pure metals and became popularized in cranioplasty. Ticonium has similar compound to vitallium but it also comprises nickel. It has advantages like ease to give shape and lightness (Sanan, 1997).

In case of a selection of an autologous bone cranioplasty, bone resorption can occur, especially when there are other complicating factors, such as longer operation time, devascularization during craniotomy, postoperative radiation therapy. Postoperative bone flap infections can result in high fever, local suppuration and potentially stubborn fistulas. In such cases, removal of the infected bone flap followed by cranioplasty using artificial bone substitutes is generally used. Another option is to perform a split bone flap from the contralateral side months after the first operation. There is still a risk of resorption of ''split bone flap'' and finally there can be an asymmetry on both donor and recipient sites (Stendel, et al., 2001).

When autologous bone is unavailable, an adequate prosthesis can be made to reconstruct the defect. The chemical composition and mechanical properties of the implant affect the acceptance and longevity of the implant. Titanium, a metallic element discovered in 1796, has been used as a cranioplasty material for many years (Gordon & Blair, 1974). A consensus in the literature presents that titanium is a good cranioplasty choice with low infection rates and good cosmesis. Moreover, titanium plate implants are relatively radiolucent and warrant high-quality postoperative CT and magnetic resonance images to be achieved. Due to the absence of resorption risks and the reality that titanium is biological inert, sustained results for patients who performed titanium cranioplasty may be more favorable in the comparison with those who have had procedures using autologous bone. Both titanium mesh and titanium implants individually prefabricated via CAD/CAM have been presented recently and have been well consented in the surgical reconstructive procedures of cranial defects (Wiggins, et al., 2013).

In this study, it is aimed to evaluate the results obtained from a selected sample patient with a titanium alloy implant used for closure of skull disorders. In this manner, it is intended to create 3D model of the patient's defected skull by using surgical simulation tools, create a prototype with the plastic modeling device and design a proper implant for the repair of the cranial defect.

Methods

The procedure for making 3D medical model consists of the following steps: patient selection, 3D digital imaging, data transfer, image processing and segmentation, evaluation of design, production and validation of the medical model. Ti6Al4V ELI (Grade 23) is selected as an implant material to evaluate the implementation and results of a cranial implant type on a patient's model. A CT-scan of the patient's fractured skull is handled and creation of 3D model of the skull implant processed by MIMICS software and surgical simulation tools. Block diagram of the process is given in Figure 1.
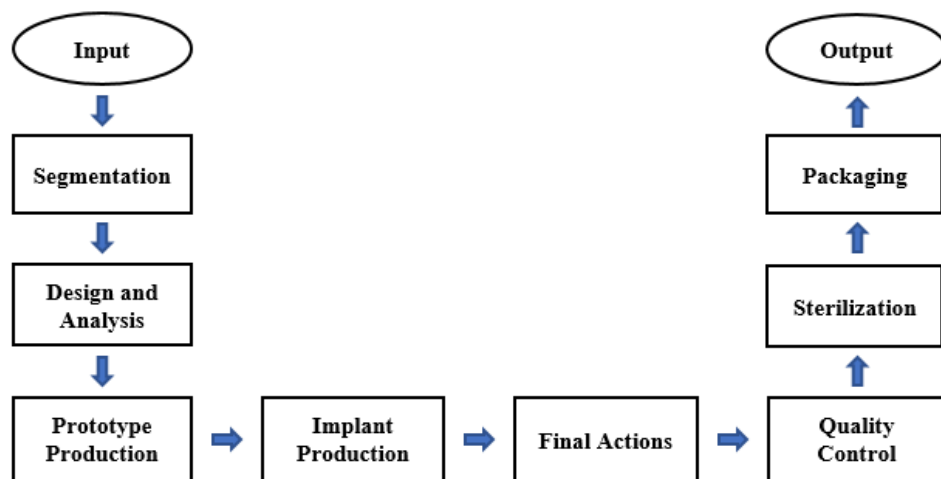

Figure 1: Block diagram of the process

In MIMICS segmentation masks are utilized to highlight the regions which must be corrected. This data is used for recreating a 3D model from the segmented structures. Under segmentation, the main tool bar consists of three tools: Thresholding, Region growing and calculation of 3D model. The first step performed to make a segmentation mask is thresholding. Predefined settings for certain biological materials are available in the thresholding toolbar. Region growing is used into the separation of the masks into different parts as well as into the getting rid of floating pixels. Calculation of 3D model is needed to transformation of the data from 2D images into 3D model.

Generally, the MIMICS Simulation Module represents a powerful 3D package for all kinds of surgery simulation applications allowed by the way of mirroring one side of the patient's skull, defining the required shape of a cranial implant is possible with the Mimics Simulation Module with its Cut, Mirror and Repositioning operations. The Mirror function mirrors all defined objects around an indicated or existing plane using the unaffected side. The selected objects are cut with a polyplane for the polyline cut operation. Then the skull is divided into two parts and a new 3D image for each of these parts is created. Lastly, the original and the mirrored parts are joined together into one part.

After the design process is completed, a surgeon approves the obtained design. Subsequently, a plastic model of the design is manufactured via Zcorp 3D Plastic Printer. The final corrections are made on this plastic model. Finally, using these new developments, Concept Laser: M2 Cusing Machine is used to produce a metallic implant by the SLS method using Ti6Al4V powder. In the next step, post-production processes of metal implant are applied.

The post processes are heat treatment, surface cleaning and polishing, quality control, **BatchProcess operation, sterilization and packaging. During the heat treatment, the implant is** baked at 840 degrees for two hours. Heat treatment is applied under protective atmosphere (with argon gas) to reduce internal residual stresses during production. Because heat treatment is used for titanium, there is a high possibility of binding (oxidization) of Ti material with O2, so during the heat treatment the material is being protected under argon gas (using oven). During the surface cleaning and polishing, sandblasting is used to dull the surface of the implant. The surface of the implant is cleaned and polished with the leveling process. During the quality control stage, the prepared product is scanned with the help of hand scanner to obtain 3D digital data of the implant. With the rapid form image, images of this data are overlapped with the XOV program and size control is performed. More than one operation can be performed with BatchProcess operation. The predefined operations are performed automatically in a programmed manner, and the results are achieved faster by avoiding time loss. Radiation sterilization is mostly used for the sterilization of thermosensitive materials and products. Heat sensitive materials and products cannot be sterilized by autoclave and dry hot air. This is because at high temperatures, the mechanical structure of the materials is damaged and the material is deformed due to the corrosive effect. The packaging method is an application required to keep the designed skull implant sterile. In a research carried out by Gupta et al. (2014), acrylic cranial implant is sterilized with ethylene oxide gas prior to the insertion.

The finite element method (FEM), also known as finite element analysis (FEA), is a numerical procedure that is used for solving problems in engineering and mathematics. The solution to boundary value problems for fractional differential equations is generally required in the resolution of these problems. A system of algebraic equations is the result of the finite element method formulation of the issue. The procedure provides approximative values of the unknowns at discrete number of points over the area. A subdivision of a large problem into smaller, simpler parts called as finite elements is made in the solution of the issue. Afterwards, the elementary equations modeling these finite elements are then united into a larger system of equations modeling the total problem. FEM makes use of variationally processes in the calculation of variations to come close to a solution by minimizing a related error function (Logan, 2011).

Shweta and Anburajan (2011) compared three biocompatible materials (titanium, steel and polymethylmethacrylate) via in the creation of a cranial implant. Similar to Shweta and Anburajan (2011), in this study, the stress analysis of titanium implant **is** performed. To determine the stress and maximum displacement distribution parameters of the titanium implant, a pressure at 1.5 MPa and 1500N load is applied to the implant. Biocompatibility tests of the obtained cranial implant are applied, finite element analysis of the titanium implant is carried out by using Patran software and statistical analysis of maximum displacement and maximum stress parameters are performed. All design, manufacturing and test procedures of implant were carried out at University of Health Science, Medical Design and Manufacturing Center (METUM).

Experimental Results

A 3D CT scan revealed the extent of the cranial defect. An accurately fit implant has been designed by using the simulation tools in MIMICS. The outer edge measurements of the implant varied between 70-100 mm. Seven screw holes which have diameter of 2mm have been placed around the plate periphery. The thickness of the implant has been set as 2.5 mm. A sample of the produced implant is given in Figure 2.
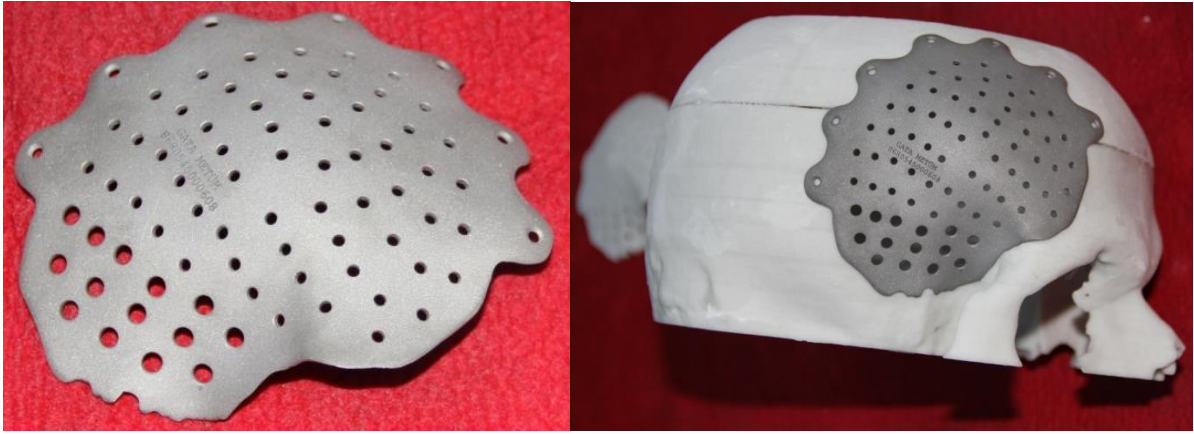
Figure 2. A Sample of Produced Metallic Implant (METUM)

Results of the Finite Element Analysis

Maximum and minimum Von Mises Stress values are found to be in the 1.349th and 24th nods, respectively. Maximal displacement and Von Mises Stress values are determined to be 62.25µ and 37.6 MPa, respectively. The results of the finite element analysis of the implant are given in Table 1.

Table 1. Showing the values of maximum displacement in µ and Von Mises Stress in MPawith1500N Load

Force: 1500N		
Material	Maximum Displacement (µ)	Von Mises Stress (MPa)
Titanium	62,25	37,6

Following the application of the load, it has been seen that the load increased towards the center of the model and the pressure is concentrated at the center (Figure 3). Figure A and Figure B are depicted as same structure but showed in different angle.
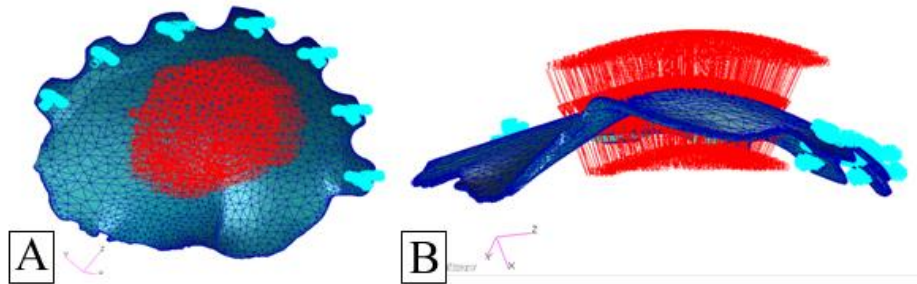

Figure 3. Load Status of the Implant Model (METUM)

Figure 4 shows the maximum displacement and stress of titanium implant material when applied 1500N load. The values obtained as a result of the static analysis are found to be in the safe working area of the material. Additionally, there is no structural problem in the implant because of the loading in the analysis conditions. In Figure 4.A, it shows Von Mises stress as front view and Figure 4.B shows back view. In Figure 4.A and Figure 4.B when it stays under maximum stress value with safety factor, material is loaded in the elastic zone appears to undergo deformation. In Figure 4.C, it shows maximum displacement as front view and Figure 4.D shows back view respectively.
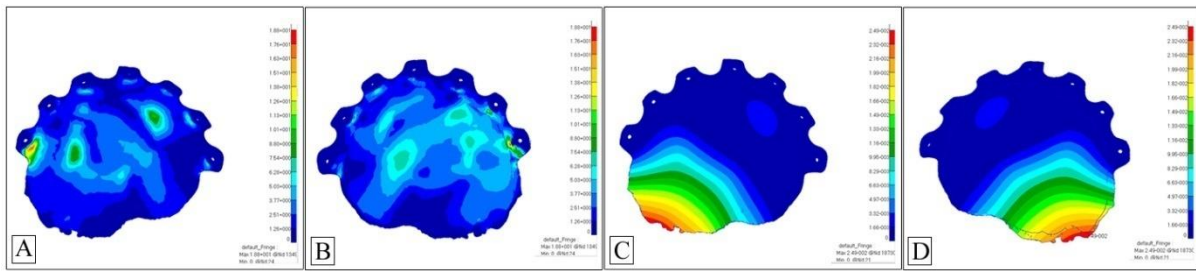
Figure 4. Von Mises Stress and Maximum Displacement of Titanium Implant Material with 1500N Load (A, C: Front View; B, D: Back View) (METUM)

The Results of Fronto-Temporo-Parietal Craniectomy

The cranium (skull) bones consist of the frontal, two parietals, temporal and occipital bones. The brain is surrounded and protected by them. The term fronto-temporo-parietal craniectomy refers to an operation where parts of the frontal, parietal and temporal bones are removed. The implant is selected to be applied in 20 years old male patient with fronto-temporo-parietal craniectomy following firearm injury. The implant is placed onto the right fronto-temporo-parietal bone and fixed to the bone with seven screws. The outcome is successful and the implant fitted precisely onto the large skull defect. Figure 5 shows the preoperative and postoperative CT-scan of the patient.
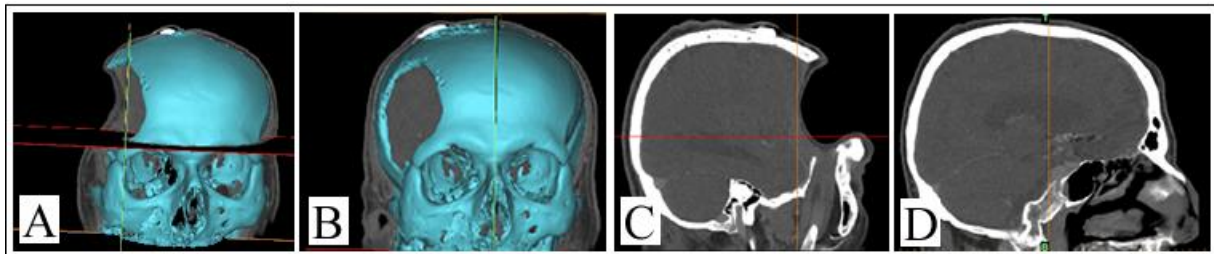

Figure 5. Preoperative CT-Scan (A, C) and Postoperative CT-Scan (B, D) of the Selected Patient with Fronto-Temporo-Parietal Craniectomy Following Firearm Injury (METUM)

Conclusion

In this study 3D model of the skull implant is made via MIMICS from the CT data. Ti6Al4V biocomposite powder is preferred as the material for implant development. Afterwards, a creation of an appropriate and accurately fit implant is produced. Finite element analysis of the implant is performed using Patran software. A pressure at 1.5 MPa is applied to titanium implant and statistical analysis of maximum displacement and maximum stress parameters are detected. The post processed implant is applied successfully in patient with a previous fronto-temporo-parietal craniectomy operation.

In our view, computer-designed, patient-specific titanium implants provide a safe, effective alternative for cranial repair when autogenous bone is unavailable. The combination of a rapid-prototype model, computer-aided design of the implant, and careful planning provided minimal surgical time and stress and an excellent cosmetic outcome for the patient. Initial results of the experiments are promising, but further studies including randomized control trials investigating different alloplastic materials for cranioplasty are needed. It would have been difficult to produce a suitable implant using conventional techniques. Ti6Al4V is the most frequently used titanium alloy in the manufacture of surgical implants. The preference of titanium instead of the alloplastic materials is because of its good biocompatibility and strength (Spetzger et al. 2010). This study demonstrates that the reconstruction of a cranial defect with a prefabricated titanium implant made by finite element assisted procedures is possible with good cosmetic results and avoidance of secondary operation.

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