Precise modeling and 3D printing of biocompatible craniofacial prostheses

Modelado preciso e impresión 3D de prótesis craneofaciales biocompatibles

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DOI: 10.35429/EJRG.2023.17.9.31.43 Received July 30, 2023; Accepted December 30, 2023

Abstract

Currently, the fabrication of accurate maxillofacial prostheses involves the integration of 3D modeling and printing technologies. This entails using tomographic scans information in (DICOM) images obtained through computed tomography "CT Scan", free-use software, and 3D printers [I, II]. These techniques are widely used by physicians and engineers, however, a generalized methodology for creating prostheses with “absolute accuracy” to patient requirements has not yet been formally established, according to Pöppe, J.P., et al. (2011) [III]. This paper shows the case of a male athlete who required implanting a large volume prosthesis in the right parietal of the Calota. The implanted prosthesis is not absolutely exact, which causes frequent headaches, in addition to being aesthetically sub-optimal. In this work, the objective is to propose a methodology that allows generating maxillofacial prostheses using DICOM images. Python libraries included in free software are used for visualization, '*.stl' stereolithographic modeling and eventual 3D printing [IV, V]. This specific case is deepened, examining each aspect in detail, and the results are compared with those of the prosthesis placed, thus contributing to improving the generation of "absolutely accurate" prostheses.

Prótesis maxilofacial, Subóptima, Tomográfica, Tomografía, Implantes craneales, Estereolitografía, Software ibre, Empleada, Metodología, Establecida, Parietal, Estética

Resumen

Actualmente se generan con éxito prótesis maxilofaciales usando modelado e impresión 3D con alto grado de precisión. Se logra mediante información en imágenes tomográficas (DICOM) obtenidas a través de tomografías computarizadas “CT Scan”, software de uso libre, e impresoras 3D [I, II]. Estas técnicas son ampliamente empleadas por médicos e ingenieros, sin embargo, aún no se ha establecido de manera formal una metodología generalizada para crear prótesis con “absoluta exactitud” a los requerimientos del paciente, según Pöppe, J.P., et al. (2011) [III]. En este trabajo se muestra el caso de un atleta masculino que se requirió implantar una prótesis de gran volumen en el parietal derecho de la Calota. La prótesis implantada no es absolutamente exacta, lo que provoca frecuentes dolores de cabeza, además que estéticamente es sub-óptima. En este trabajo, se plantea como objetivo proponer una metodología que permita generar prótesis maxilofaciales utilizando imágenes DICOM. Se emplean bibliotecas de Python incluidas en software libre para visualización, modelado estereolitográfico ‘*.stl’ y su eventual impresión 3D [IV, V]. Se profundiza en este caso específico, examinando detalladamente cada aspecto, y se comparan los resultados con los de la prótesis colocada, contribuyendo así a mejorar la generación de prótesis de "absoluta exactitud".

Maxillofacial prosthetics, Suboptimal, Tomographic, Tomography, Cranial implants, Stereolithography, Free software, Employed, Methodology, Established, Parietal, Aesthetics

Citation: HERNÁNDEZ-MALDONADO, Victor Miguel & RIOS-SOLIS, Leonardo. Precise modeling and 3D printing of biocompatible craniofacial prostheses. ECORFAN Journal-Republic of Guatemala. 2023. 9-17:31-43.

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Introduction

Traumatic brain injury (TBI) represents a widespread reason for emergency department visits worldwide, and it carries significant consequences in terms of both disability and mortality. Brain imaging, specifically using CT scans, plays a crucial role in the management of TBI. Moreover, it greatly aids in the identification of traumatic brain injuries, as illustrated in Figure 1. Consequently, on a global scale, the prevalence of trauma results in approximately 1.2 million fatalities and a range of 20 to 50 million non-fatal cases annually. This, in turn, establishes trauma as the primary contributor to disability. In the specific context of Latin America, the mortality rate stands at 38.8 deaths per 100,000 inhabitants, positioning it as the fourth most common cause of death [V]. These concerns predominantly affect males with an average age of around 34.3 years. Furthermore, approximately one-third of survivors will experience significant sequelae, and only 40% will successfully reintegrate into their occupational roles. In conclusion, a discriminative reflective model has been demonstrated, offering the capacity to prognosticate outcomes pertaining to severe disability, vegetative state, and mortality among individuals afflicted by traumatic brain injury. This predictive model stands as a reliable tool applicable within clinical environments. Consequently, this innovation holds the potential to instill a high degree of confidence in its utilization within medical practice. [VI].

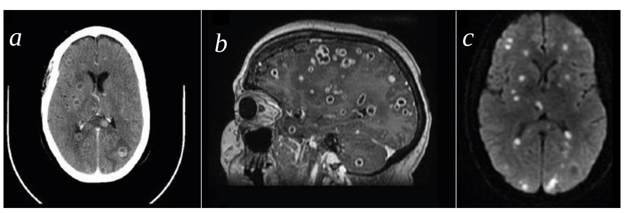

Figure 1 Image example of CTScan (computed tomography) (a) Represents axial section with skull bone, (b) Sagittal section, (c) Axial section without skull bone. *Source: Figure extracted from Multiple brain abscesses due to Streptococcus milleri. Revista de Neurología [VII].*

This subject is of pertinent importance, wielding a substantial influence on Mexican societal dynamics. Primarily, it engenders ramifications for the afflicted individual as the central casualty, along with their familial network, which becomes encumbered with the financial burdens of hospitalization, surgical procedures, provision of prosthetics, and diverse rehabilitation regimens.

Furthermore, not only does it impact governmental bodies and commercial enterprises, but it also has a consequential effect when prolonged disability afflicts an employee, resulting in a 33% probability of encountering notable lingering consequences. Consequently, the multifaceted repercussions of this phenomenon permeate various strata of Mexican society.

In this investigation, our primary emphasis is directed toward formulating a methodology with the specific objective of fabricating a prosthetic apparatus that impeccably aligns with the precise requisites of the patient [III]. The cardinal novelty inherent in this scholarly inquiry resides in the exclusive utilization of publicly accessible, specialized computational tools. These tools empower designers, engineers, or medical practitioners to craft a prosthetic device distinguished by this singular attribute of unequivocal precision. Moreover, the prosthetic construct engendered through the delineated procedure must encompass four designated attributes [VIII]:

a) Comparatively economical.

b) Pleasing in its aesthetic manifestation.

c) Exhibiting commendable functionality.

d) Pertaining to the production of prostheses tailored in accordance with the morphological attributes of the individual. Consequently, the pursuit of these endeavors epitomizes a substantial advancement in the domain of prosthetic development.

Three-dimensional (3D) printing or Additive Manufacturing (AM) is a group of fabrication processes where three-dimensional parts are constructed by adding layers of bondable materials on point, line, or planar surfaces [IX, X]. a swiftly developing technology, has brought about transformative changes across multiple sectors, particularly medicine and surgery. This advancement in medical applications has been facilitated by the convergence of progress in manufacturing technologies, cross-sectional imaging, user-friendly medical 3D computer-aided design (CAD) software and expanding clinical indications.

The capacity to fabricate accurate, patient-specific anatomical and pathological models has propelled enhancements in surgical preoperative planning, intraoperative decision-making, education, and the design of both customized and commercially available 3D-printed implants. In synergy with novel surgical methodologies, 3D printing has contributed to addressing increasingly intricate spinal deformities, refining outcomes during complex oncological resections, and enabling the production of bespoke implants [XI].

Finally, the fundamental necessity for achieving precise medical prostheses is contingent upon the provisioning of medically customized remedies harmonized with the intricate subtleties of human anatomy. This juxtaposes significantly against conventional medical apparatuses, which lack the capability to accommodate individualized prerequisites and are characterized by their elevated financial implications. Consequently, a pressing need emerges for pioneering fabrication approaches within the domain of tailored precision medicine. This imperative is underscored by the overarching aspirations of curbing financial burdens and enhancing operational efficiency [XII]. Moreover, the emergence of such methodologies bears substantial implications for the landscape of medical intervention.

The DICOM format

The DICOM format (Digital Imaging and Communications in Medicine) is a standard used for the exchange of medical images and related data in clinical settings. DICOM provides a common file format that allows different medical devices, such as magnetic resonance machines, computed tomography scanners, and ultrasound systems, to capture, store, transmit, and display medical images in an interoperable manner The data compilation encompasses additional metadata, encompassing a comprehensive range of attributes including, but not confined to, pixel data particulars as well as pertinent patient demographics like nomenclature, gender, age, mass, and stature. The caliber of medical images stands as an exceedingly pivotal determinant, exhibiting a profound correlation with the precision of diagnostic interpretations and practicability. [XIII].

Consequently, the medical sphere necessitates substantial storage capacity for perpetuating long-term archival pursuits. Moreover, this mandates the implementation of streamlined communication mechanisms adept at expediently transmitting these images. The intricate interplay of these elements forms an integral aspect of the medical landscape. [XIII].

Primarily, DICOM establishes a coherent set of regulations and protocols aimed at guaranteeing harmony and uniformity within the realm of medical image communication. It delineates the stipulations governing the storage of image data and outlines the architecture and structure of accompanying metadata, encapsulating crucial elements like patient specifics, acquisition methodologies, and distinct image attributes. Consequently, this framework ensures the accessibility and accurate interpretation of pertinent clinical data across disparate medical systems and applications. Moreover, it expedites the assimilation of medical images into Health Information Systems (HIS) and Picture Archiving and Communication Systems (PACS). Through the adoption of the DICOM framework, a seamless exchange of images and their associated data becomes feasible across diverse devices and healthcare settings. This, in turn, fosters heightened collaboration and facilitates unimpeded access to clinical insights. This facet assumes paramount importance, especially within contexts demanding the sharing of images among hospitals, clinics, and specialized practitioners for purposes of patient diagnosis, therapeutic interventions, and post-treatment monitoring. Thirdly, DICOM encompasses comprehensive standards encompassing the visualization and manipulation of medical images. It delineates the manner in which images ought to be rendered in terms of grayscale dynamics, annotations, quantifications, and image processing utilities. This meticulous standardization guarantees that medical professionals and healthcare providers can accurately and consistently decipher and assess images, irrespective of the platform or visualization instrument at their disposal [XIII]. This multi-faceted orchestration, rooted in the DICOM framework, orchestrates a symphony of interoperability and precision across the complex landscape of medical imaging.

ISSN-On line: 2414-8849

In synopsis, the DICOM format stands as an elemental benchmark within the realm of medical imaging, affording a secure and dependable avenue for the seamless transmission of images and correlated data across heterogeneous devices and healthcare infrastructures. This format not only fosters interoperability but also amplifies collaborative capacities, thereby securing the precision of medical image interpretation. Consequently, this pivotal standard engenders an advancement in patient care and therapeutic interventions. Moreover, the multifaceted influence of the DICOM format traverses the intricate expanse of medical practice.

Visualization of DICOM images with free software

DICOM images necessitate rendering through dedicated software entities recognized as DICOM viewers, adept at comprehending and presenting this specialized format. These images, in conjunction with their correlated patient particulars, commonly find their repository within an expansive repository denoted as a Picture Archiving and Communication System (PACS). The reason for being a DICOM application resides in its ability to stockpile comprehensive insights within the PACS pertaining to the imaging exploration, alongside pertinent patient attributes. Subsequently, when requisite, these applications facilitate the visual examination, interpretation, and potentially even manipulation of the medical images procured from the PACS. The distinctive attribute of DICOM images rests in their fusion of patient-specific information and the actual image data. Consequently, the intrinsic character of DICOM images not only encapsulates visual data but also serves as a conduit for conveying indispensable clinical details.

A broad spectrum of software applications, libraries, and open-source platforms is accessible for the purpose of visualizing DICOM images. Moreover, several of the preeminent options encompass:

1. InVersalius [XIV]
2. OsiriX
3. Blue Sky Plan 4 [XV]
4. 3D Slicer [XVI]
5. Ginkgo CADx
6. MedDream DICOM Viewer
7. MicroDicom
8. RadiAnt DICOM Viewer
9. DICOMscope
10. Sante DICOM Viewer Free
11. Mango
12. GDCM (Grassroots DICOM)
13. DicomBrowser

Methodology

Visualization and generation of the stereolithographic model

a) The beginning of this investigation involves the acquisition of tomographic studies conducted within the pertinent medical institution or clinical domain, subsequent to obtaining requisite consent from the patient and/or their familial representatives. Upon the acquisition of this dataset, either Blue Sky Plan 4 (developed by Blue Sky Bio, USA) or 3D Slicer 5.2.2 is employed. Notably, both of these software applications produce analogous visualization outcomes, as evidenced by the illustration in Figure 2. Consequently, the selection of either of these programs offers consistent visualization results for the undertaken analyses.

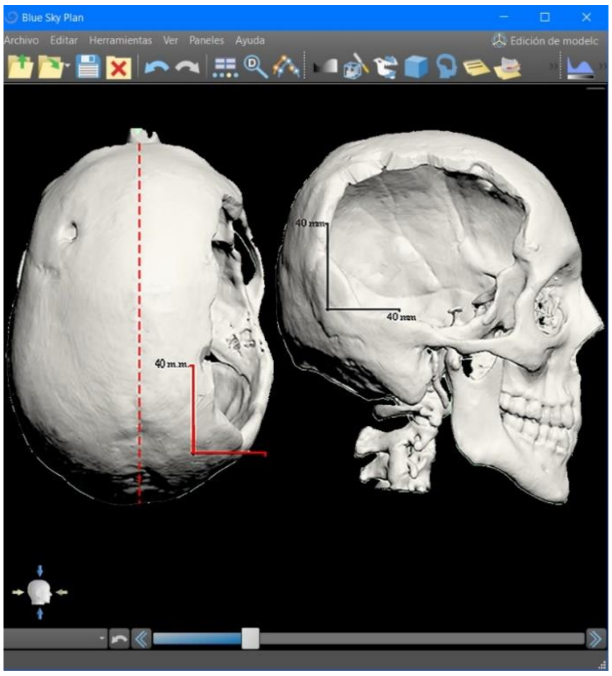

Figure 2 Visualization of tomography in Blue Sky Plan 4 software (Blue Sky Bio, EE. UU.) (Left) superior view, (Right) right lateral view, cavity of the prosthesis. This figure was created in Blue Sky Plan 4 software

b) The selection of software is contingent upon the specific exigencies and predilections of the user. For the purpose of exporting the '.stl' model, our focus converged on both Blue Sky Plan 4 [XV] and Slicer 5.2.2 [XVI]. These two open-source software platforms are notable for their utilization of Python libraries, each equipped with its dedicated Python console. This console interface empowers users to adeptly manipulate commands, thereby streamlining tasks associated with visualization and the formulation of *'.stl'* files. Furthermore, it is noteworthy that a substantial corpus of documentation is at the disposal of users, elaborating on the intricacies of their operational paradigms. The generation of the '*.stl' model is subsequently executed via the "create model" directive integrated within the Blue Sky Plan 4 software, a depiction of which is portrayed in Figure 3. Swiftly and efficiently, this command engenders the model, positioning it within the directory designated by the user. Consequently, the adoption of either of these software platforms facilitates the swift and precise generation of the target model, aligned with user-specific stipulations.

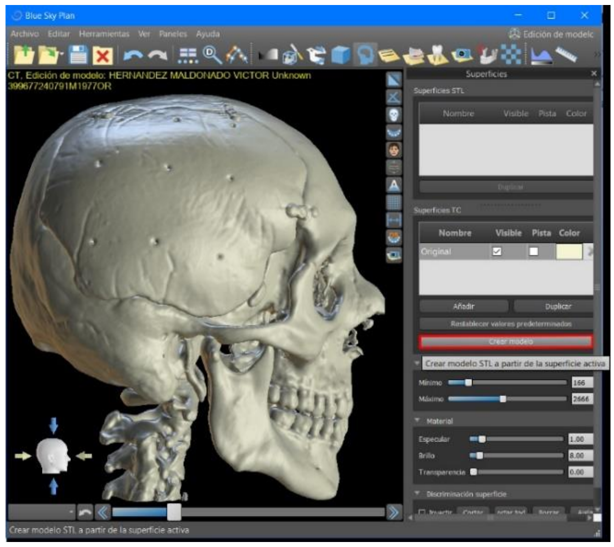

Figure 3 Generation of the '*.stl' model with the Blue Sky Plan 4 software (Blue Sky Bio, EE. UU.) This figure was created in Blue Sky Plan 4

Consequently, this marks the culmination of the visualization and extraction process for the '*.stl' model.

Refining the model and obtaining the final prosthesis

Moreover, the patient manifests a distinctive attribute within their case, necessitating the application of two distinct prosthetic interventions across both hemispheres of their cranial structure. The initial and more imperative prosthesis finds its placement on the right parietal region, which previously underwent a craniotomy procedure. Equally imperative is the requirement for a perforation on the left frontal region to accommodate a drainage valve. Both of these prerequisites are graphically elucidated in Figure 4, demarcated by the dashed red line.

To start, we direct our attention to the scenario entailing the craniotomy-related prosthesis. Evidently, meticulous preoperative strategizing is essential to optimize the design of this prosthesis. The inaugural phase involves the utilization of a computed tomography (CT) scan of the patient's cranium. The purpose here is to conceptualize an implant tailored to the affected area, i.e., the right parietal region of the cranial anatomy, as visually represented in Figure 4.

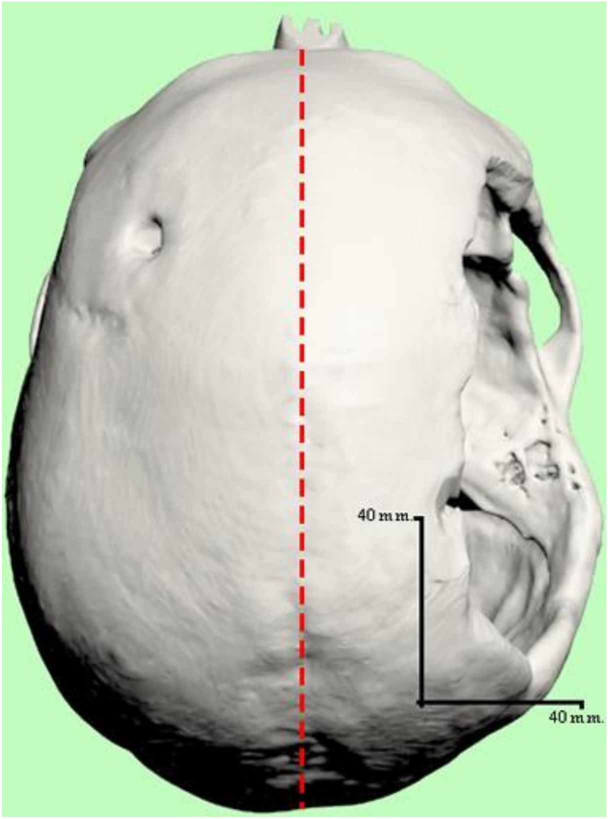

Figure 4 Displays a CtScan of the patient from a superior viewpoint. The left side depicts a healthy skull, while the right side reveals a huge absence or loss. This figure was created in 3DS Max 2023

The procedure for designing entailed the implementation of the mirroring technique, which involved referencing the intact side of the skull (depicted in Figure 4; situated on the left side of the dashed red line). This approach ensured the alignment of the skull while concurrently establishing the precise orientation for the cranial implant. This methodology is visually illustrated in Figure 5. Moreover, this strategy is pivotal in achieving accurate implant alignment and positioning.

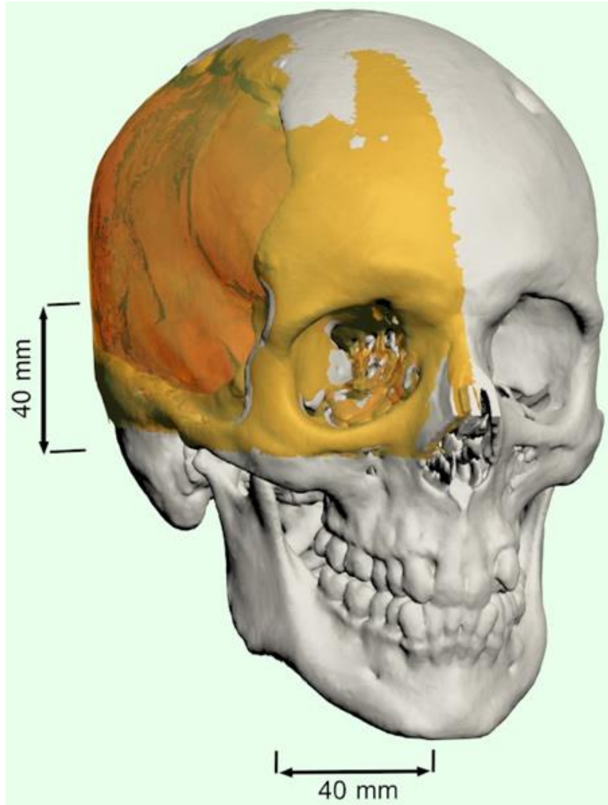

Figure 5 Displays a contrast between both zones, the healthy and the loss of bone. This figure was created in 3DS Max 2023

The mirroring technique appears to yield promising results, and now it is time to exclusively model the area that the prosthesis covers.

It is of utmost importance to carefully adhere to the boundary set by the skull or recipient matrix when designing the prosthesis model. This aspect represents the major contribution of this study. While certain functionalities within Python software, such as Slicer 3D 5.22, are harnessed to execute this task, the resultant prosthesis does not attain the state of "absolute accuracy" as defined by Pöppe, J.P., et al. [III]. Consequently, there remains a potential divergence between the final fabricated prosthesis and the precise contours of the recipient's cranial architecture. This discrepancy underscores the imperative for further refinements in pursuit of enhanced precision.

Therefore, the suggested methodology can be outlined as follows:

1. Meticulously trim the surplus region that intersects between the prosthesis model and the recipient matrix, with careful consideration for precision and alignment.

2. Subsequently, it becomes imperative to ensure the "closure" of the model, guaranteeing absolute continuity of the surface of the prosthesis model. In essence, the stereolithographic rendition must be devoid of any gaps or disruptions in its mesh structure.

3. This necessity arises due to the mirroring technique employed in modeling from the CT scan (depicted in Figure 5), which does not perceive the cranial osseous system as a cohesive entity with a wholly continuous surface. Instead, it results in the generation of an empty mesh, introducing a void between the internal and external surfaces, or even between both sides of the cranium. The problem of this predicament resides in the inadequacy of this approach for the purposes of fabrication, as a consistent mesh is imperative for comprehensive printing considerations. It is essential that the mesh maintains continuity across all facets of the cranial anatomy, encompassing both surfaces and the structural thickness of the skull. Consequently, the procedural guidelines elucidated, become indispensable in addressing this exigency.

4. During this phase, it becomes apparent that certain regions within the mesh of the prosthetic model persist in overlapping with the patient's cranial structure. These overlapped discrepancies have the potential to engender complications in the event of the prosthesis being "intersected" by the patient's skull during the printing process. Consequently, these regions are pinpointed, and the vertices of the mesh are subject to manual modification or manipulation to rectify these imperfections. This meticulous adjustment is essential to ensure a precise and seamless fit of the fabricated prosthesis onto the recipient's anatomy.

5. In the ultimate stage, the Spline interpolation technique is deployed, leveraging a mathematical function to estimate values with the goal of minimizing the aggregate curvature of the surface. As a corollary, a polished and continuous surface is engendered, meticulously traversing the input points [XIII]. This intricate procedure serves to eradicate irregularities within the prosthesis, the presence of which could potentially instigate persistent cephalgia for the patient. Such irregularities might inadvertently interact with tender regions of the scalp, eliciting sensations of discomfort.

6. The application of the Spline interpolation method thus bears significance in refining the prosthetic structure to ensure patient comfort and satisfaction.

Results

Primarily, it is imperative to comprehend the aftermath of the prosthesis that has been surgically embedded within the patient. This outcome is elucidated through the depiction in Figure 6, which accentuates the regions where the prosthesis does not achieve a seamless integration with the contours of the patient's cranial architecture. This incongruity engenders a lack of continuity, resulting in a persistent and vexing manifestation of headaches that the patient must continually contend with.

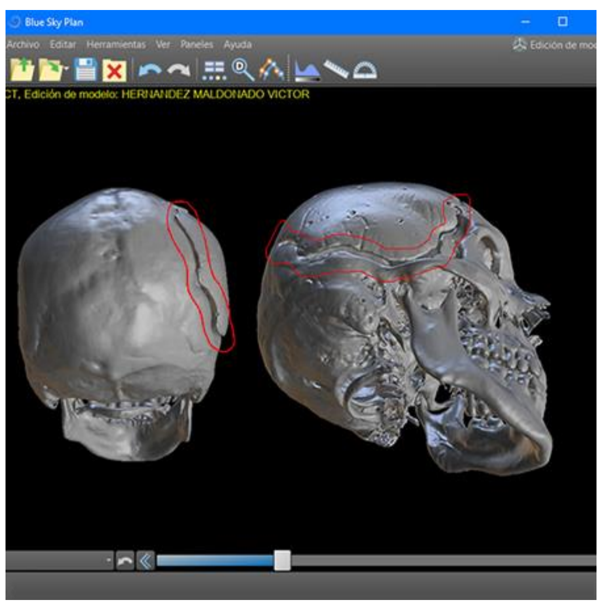

Figure 6 The presented image displays the prosthesis that has been placed on the patient. Additionally, the red highlighting emphasizes the discontinuity between the prosthesis and the skull's boundary. This figure was created in Blue Sky Plan 4

The outcomes of the methodology expounded are visually presented. Figure 5 exemplifies the utilization of the mirroring technique to reinstate the region influenced by the craniotomy. Within this illustration, it becomes discernible that a substantial portion of the "cloned" mesh redundantly intersects with the patient's cranial structure, as conspicuously observed around the right eye socket. Moreover, Figure 7 offers a comprehensive portrayal of the results emanating from the application of steps 1, 2 and 3.

This illustration unveils the efficacious elimination of superfluous material, concurrently affording a proximate representation of the ultimate implanted prosthesis model. This cascade of visual depictions contributes to an enhanced comprehension of the procedural evolution and its resultant impact on the prosthesis fabrication process.

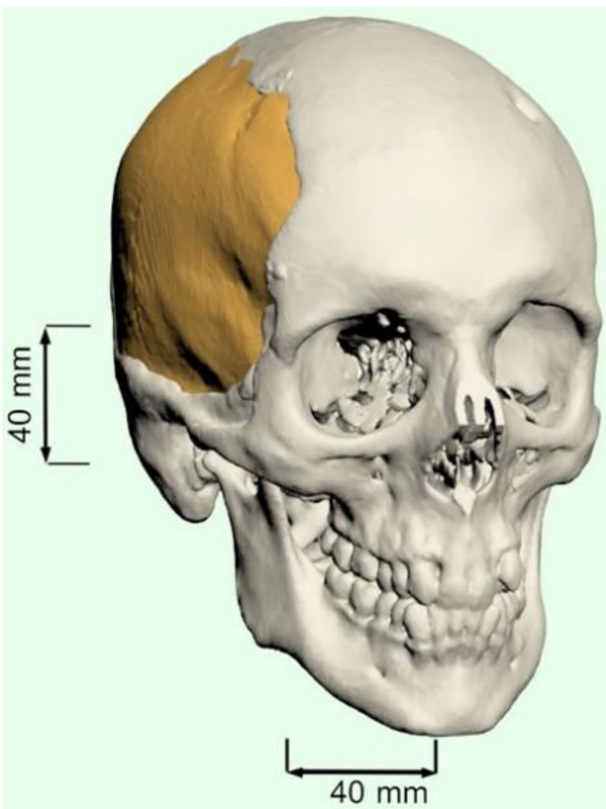

Figure 7 Displays the result of steps 1, 2 and 3; The excess mesh of the prosthesis was trimmed. This figure was created in 3DS Max 2023

In a concluding illustration, Figure 8 serves to exhibit the finalized prosthesis model, having undergone the comprehensive closure and smoothing processes detailed in step 4. Furthermore, the entirety of the cranial structure is depicted, rendered with a pronounced level of transparency.

This strategic visualization technique is employed to accentuate the prosthesis, distinctly demarcating its presence and pinpointing its precise location within the context of the entire skull. This multifaceted visualization aids in elucidating the integration and alignment of the prosthesis within the recipient's cranial anatomy.

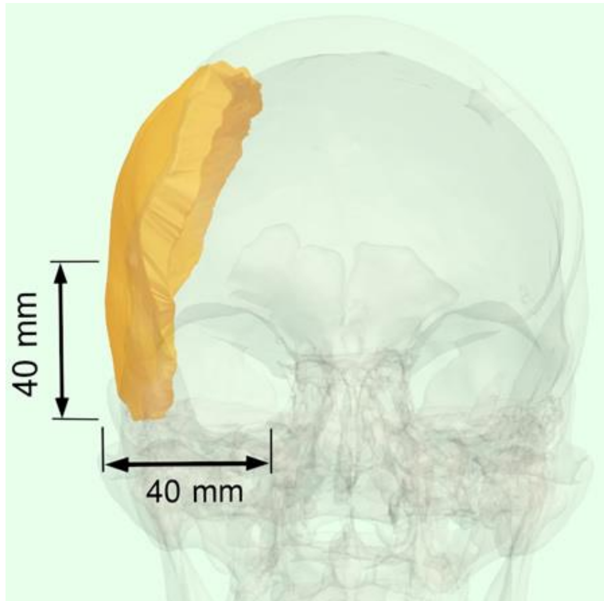

Figure 8 The completed prosthesis is presented, demonstrating the desired softening effect. This figure was created in 3DS Max 2023.

Subsequently, our attention turns to the scenario involving the second prosthesis, whose function is to cover a perforation on the left frontal section. This perforation was necessitated by the insertion of a drainage valve, a depiction of which is evident in Figure 9. This pivotal context underscores the distinct focus of the ensuing analysis and design considerations.

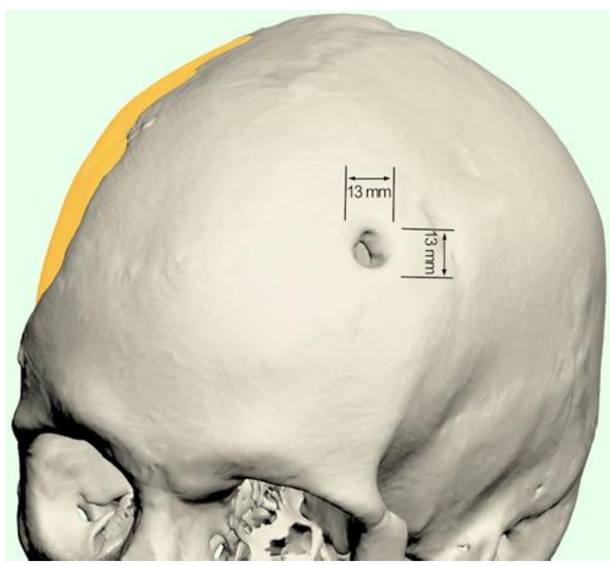

Figure 9 Perforation occurred due to inserting the drain valve in the left frontal bone. This figure was created in 3DS Max 2023

Figure 10 displays the outcome of applying steps 1, 2, 3, and 4 for the creation of the "plug" prosthesis for the left frontal bone.

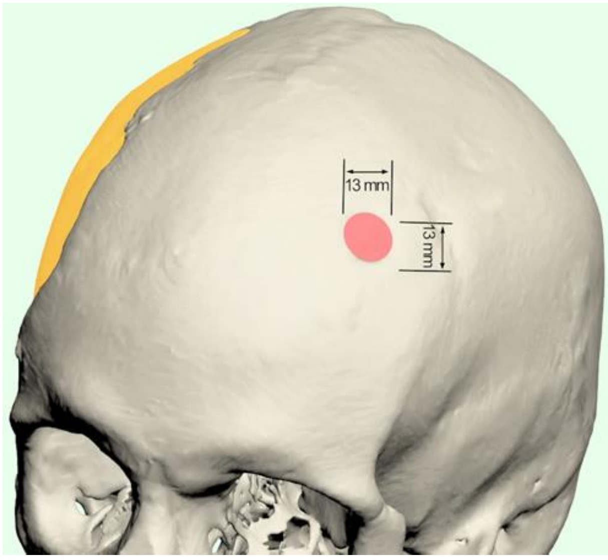

Figure 10 Perforation occurred due to inserting the drain valve in the left frontal bone. This figure was created in 3DS Max 2023

In pursuit of the objective of visually representing both prostheses, Figure 11 serves to present the two finalized prosthesis models, each having undergone the requisite closure and smoothing procedures. Additionally, the entirety of the cranial structure is unveiled, characterized by a notable degree of transparency. This visual depiction strategy is strategically employed to underscore the presence and significance of both prostheses, distinctly highlighting their individual locations within the overall cranial framework. This comprehensive visualization endeavor significantly contributes to enhancing the understanding of the spatial dynamics and alignment of the two prostheses within the anatomical context.

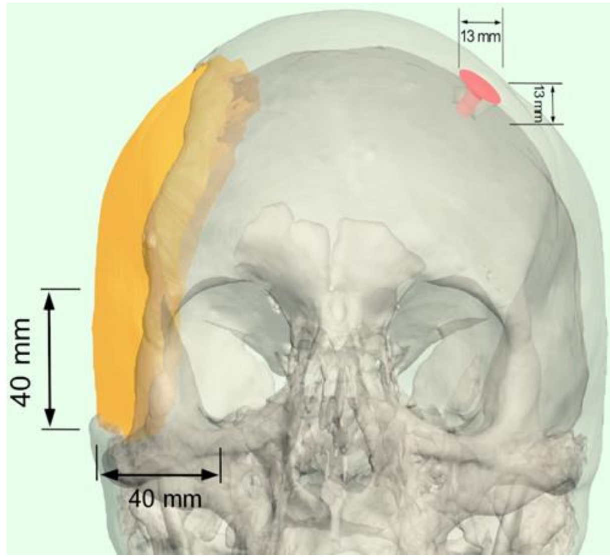

Figure 11 They are shown both prosthesis models. On the left side, it is shown the bigger prosthesis, on the right side the 'plug' prosthesis is shown; the rest of the skull is shown with a transparent effect. This figure was created in 3DS Max 2023

3D printing applications in the near future

The advent of versatile biomaterials possessing intrinsic and specialized functionalities alongside distinct biological impacts satisfactorily fulfills the requisites of diverse biomedical utilization [XVII].

As we know, neoplasms pose a significant peril to human well-being. Concurrent with global demographic aging and shifts in environmental and behavioral patterns, the annual incidence of cancer-related mortalities exhibits a rising trend. Thus, the international community finds itself enmeshed in a critical confrontation with the formidable adversary of cancer [XVIII].

In light of this circumstance, the management of tumor treatment conditions has emerged as a pivotal endeavor for the scientific community. Within the scope of cancer therapeutics, chemotherapy assumes an indispensable function. Regrettably, numerous extant pharmacotherapeutic agents targeting tumors manifest inherent challenges encompassing pronounced hydrophobic characteristics, limited systemic absorption, heightened cytotoxicity, and deleterious secondary outcomes, thereby impeding their alignment with the requisites of efficacious cancer treatment. Consequently, a preeminent imperative in our agenda involves the fabrication of an adept and minimally cytotoxic conduit for dispensing antineoplastic agents.

Formulations characterized by sustained and/or targeted release mechanisms afford the advantage of protracted and concentrated exposition of neoplastic tissue to therapeutic drug moieties. This strategic modality circumvents the exigency of recurrent dosing, concomitantly attenuating the toxicity profile and untoward repercussions associated with antineoplastic interventions. In contrast with conventional pharmaceutical techniques, three-dimensional (3D) printed pharmaceuticals offer pivotal merits encompassing malleable tailoring and meticulous dose regulation. The capacity for "just-in-time" generation of pharmaceutical constructs utilizing 3D printing modalities obviates the constraints inherent in the conventional paradigm of uniform manufacturing processes, thereby aptly addressing the personalized therapeutic requisites dictated by distinct patient parameters including age, body mass, organ functionality, and disease acuity [XVIII].

Additive manufacturing (AM), commonly known as 3D printing, represents a paradigm-shifting strategy within industrial domains. It constitutes a novel digital process characterized by the successive deposition of materials to form intricate three-dimensional configurations based on digitalized 3D schematics. In the contemporary milieu, the biomedical sphere has become an arena of paramount significance for 3D printing, epitomizing a versatile and environmentally conscientious technique for engendering intricate geometries germane to healthcare domains. The prowess of additive manufacturing materializes in the provision of highly personalized and patient-specific anatomical constructs, presenting an innovative and tailored therapeutic avenue for individual patients. This technology finds exceptional utility within the medical sciences, facilitating the fabrication of surgical and medical apparatuses, prosthetic constructs, and bespoke implants tailored to the anatomical demands of diverse corporeal regions. Its utilization in the medical domain spans disciplines such as orthopedics, dentistry, and the engineering of surgical instrumentation encompassing items like eyeglass frames and lenses.

Beyond its conventional biomedical applications, additive manufacturing has extended its purview to encompass progressive facets like the three-dimensional bioprinting of living cellular and tissue structures. Furthermore, the prevalence of customer-centric requisites within the biomedical milieu, particularly in the realm of prosthetics, has amplified the prominence of additive manufacturing's role [XIX].

This technological advancement thus experiences a burgeoning trajectory in the creation of patient-specific implants and prosthetic solutions, fundamentally redefining the landscape of tailored healthcare solutions.

A diverse array of substances finds application in the additive manufacturing realm, encompassing constituents such as acrylonitrile–butadiene–styrene, nylon, polylactic acid, wood, rubber, and ceramics, among others. This underlines the wide-ranging spectrum of printable materials, ranging from plastic filaments to metallic and carbon powders, as well as hydrogels. This inherent versatility in both the 3D printing materials and the process itself engenders its extensive utilization, surpassing that of conventional methodologies.

The present quandary confronting 3D printing technology within the biomedical domain pertains to the fabrication of materials through this process. Predominantly, the challenges are concentrated in the judicious selection of binding agents and compatible printers. The attainment of desired end products hinges on the choice of an apt binder during the material curation process. In the context of biodegradable 3D printed materials, the binder necessitates attributes of non-toxicity, biodegradability, and operational feasibility; however, a binder possessing the complete suite of these attributes proves to be an elusive proposition. Consequently, the task of identifying a fitting binder suited for the 3D printing of biomedical devices remains a formidable undertaking in this domain [XIX].

Conclusions

This study leveraged two aspects that are readily available for research: Firstly, the current momentum in the field of maxillofacial prosthesis manufacturing using open-source software for modeling and creating stereolithographic files, along with 3D printing.

ISSN-On line: 2414-8849

Secondly, the significant number of cases in Mexico and worldwide makes traumatic brain injury one of the leading causes of death. Consequently, there is a great need for the population to generate high-quality and cost-effective prostheses.

The second aspect pertains to having the author's own case as a study subject, which provided access to tomographic studies and the input of healthcare professionals, particularly traumatologists and neurosurgeons. As mentioned in the body of this work, the patient suffers from constant headaches primarily caused by the inaccurate positioning of the prosthesis, which is misaligned with the skull bone, as shown in Figure 6.

This imprecision motivated the author to explore options for generating maxillofacial prostheses, as stated by Pöppe, J.P., et al. [III], which must be of "absolute precision."

In addition, the flexibility of 3D printing materials allows the selection of biocompatible options tailored to the individual needs of patients. Integrating 3D printing technology into orthopedic and prosthetic patient care improves the efficiency of the device manufacturing process while ensuring customized solutions that optimize patient outcomes [XVIII].

The next step in this research is the printing or generation of the "plug" prosthesis using biocompatible materials, which will be implanted through a surgical intervention in the patient to observe their reaction and determine the feasibility of the entire process.

Future research involves the utilization of artificial intelligence (AI), as demonstrated by da Rocha et al. (2022) [XX], to implement the method proposed here and generate prostheses of absolute precision.

Funding sources

This work has been exclusively funded by Infotec, it does not have a grant number.

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