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Use of computer tomography and 3DP Rapid Prototyping technique in cranioplasty planning – analysis of accuracy of bone defect modelling

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Summary

Background: The accuracy considerations of alignment of skull bone loss and artificial model of implant are presented. In standard surgical treatment the application of prefabricated alloplastic implants requires complicated procedures during surgery, especially additional geometry processing to provide better adjustment of implant. Rapid Prototyping can be used as an effective tool to generate complex 3D medical models and to improve and simplify surgical treatment planning. The operation time can also be significantly reduced. The aim of the study is adjustment accuracy analysis by measurements of fissure between the bone loss and implant.

Material/Methods: The 3D numerical model was obtained from CT imaging with Siemens Sensation 10 CT scanner. The physical models were fabricated with 3DP Rapid Prototyping technology. The measurements were performed in determined points of the bone loss and implant borders.

Results: Maximal width of fissure between bone loss and implant was 1.8 mm and minimal 0 mm. Average width was 0.714 mm, standard deviation 0.663 mm.

Conclusions: Accuracy of 3DP technique is enough to create medical models in selected field of medicine. Models created using RP methods may be then used to produce implants of biocompatible material, for example by vacuum casting. Using of method suggested may allow shortening of presurgery and surgery time.

Key words: **computed tomography (CT) • rapid prototyping (RP) • craniectomy**

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Background

Rapid prototyping is a construction of a prototypical physical object (single) with the use of a 3D digital model consisting of a spatial grid composed of triangles representing the surface of the object. The saving format of such a file is called STL (STereoLitography) and is commonly known in technological environments as an input format of data for the majority of RP machines.

Computed tomography, being an imaging technique of a high spatial resolution, allows for a construction of numerical models of specific human body parts, with an accuracy appropriate for medical modelling [1,2]. These models, together with the methods of rapid prototyping, enable the scientists to construct functional prototypes of all kind of prostheses and implants for medical purposes.

One of the potential applications of RP is designing the prosthetic restoration of cranial bone defects, for the purposes of cranioplasty. To create such a model, one of the RP techniques can be used – 3DP (3D Printing) [3]. This is financially profitable [4]. A very important issue is also the accurate performance of a suitable prosthetic element [5,6].

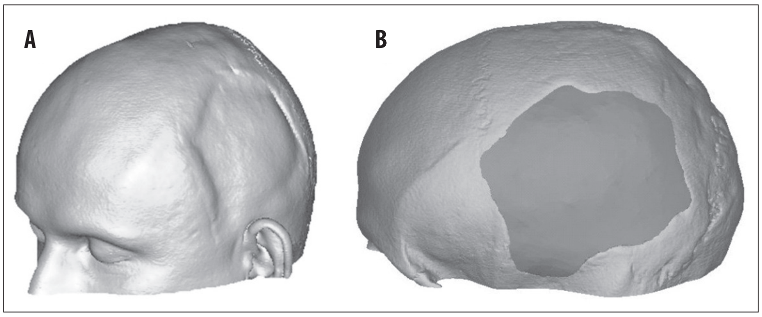

Figure 1. Generated STL surface model: (**A**) head shape reproduction with a visible defect (**B**) skull fragment defect and implant project models.

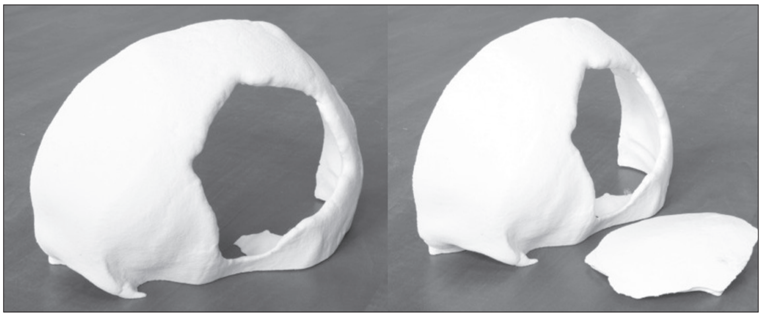

Figure 2. Physical models of defect and implant.

The aim of the work was to analyse the accuracy of the adjustment of the projected prosthetic elements (implants), for the purposes of cranioplasty, performed with a 3DP technology, and to analyse the surface of contact of cranial bone defect.

Material and methods

Data acquisition – preparation of a numerical model

The data set in the form of a raster graphics image is a basis for a 3D vector model. We collected these data in the process of acquisition, with the use of a multi-row-detector spiral CT scanner by Siemens Sensation 10. The region of scanning included head with cranial bone defect (Figure 1A). We prepared the numerical model and processed it with the use of 3D-DOCTOR software by Able Software Corp.

The obtained 2D images were subjected to segmentation, i.e. selection of elements constituting the basis for the construction of a model of the cranium part with the defect. Contour images generated on the basis of such segmentation included information about the outer and inner edges of the selected elements. The collection of cross-sections was used to create a 3D presentation in the form of a spatial grid composed of triangles representing the surface of the object, in the STL format (STereoLitography).

The conversion of data to a surface model allowed for a full model manipulation in CAD systems, addition of some extra geometrical features or construction of a model of prosthetic restoration of a bone defect (Figure 1B).

Construction of a physical model of the cranial bone defect with the 3DP method

The obtained numerical model constituted a basis for the physical model of the implant, performed with 3DP technique (Figure 2). The technology of this process based on the creation of layers forming the model. The CAD (STL) model may be segmented; each segment includes specific information on the geometry of one layer (2D). The subsequent layers of the model are created by laying down the layers of a powder. 3DP technology is similar to the process of ink printing; the binder cements the powder with the previous layer only in the point in which the model is to be formed. Then, the platform descends, allowing for an application of the next layer of the powder which will get bound with the previous one. The process repeats until the creation of the model of the whole object. After removing the remaining reinforcing material – the unbound powder – the object gets infiltrated. The type of infiltrator influences the mechanical properties of the model [3,4].

The model was created with the use of a 3DP Z510 apparatus by ZCorp.

The analysis of accuracy in alignment of the implant edges

The model of bone defect prosthesis was adjusted with the use of Materialise Magics program. The part of the model of the undamaged side of the cranium was symmetrically mirror-reflected against the medial body axis; next, the area of the defect was deducted. As a result, we obtained a digital model of the prosthetic element (implant) reconstructing the cranial bone defect. The analysis of the accuracy of the alignment between the implant and the model of the defect was carried out in 18 selected points, situated along the edge of the defect (Figures 3,4). The measurements were performed with an optical reflection-light microscope, Dino-Lite Digital Microscope PRO AM413T, using 60× zoom (Figure 5).

Results

Table 1 presents results on model adjustment.

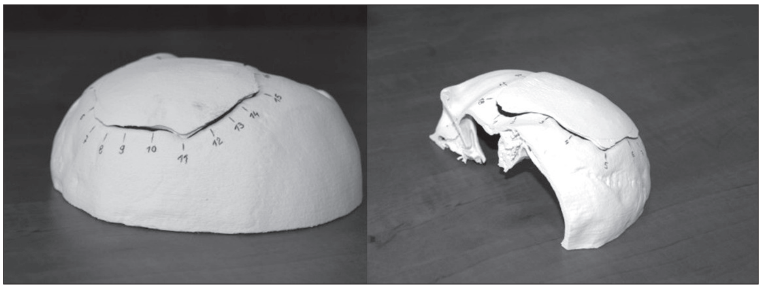

Figure 3. Prototype of defect with implant, measurement points marked (implant image before fixation, for better presentation).

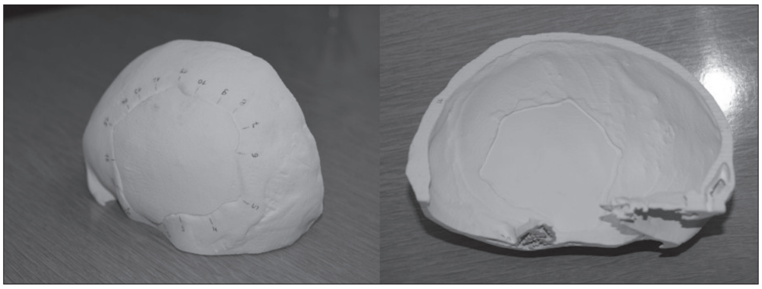

Figure 4. Prototype of defect with a mounted implant.

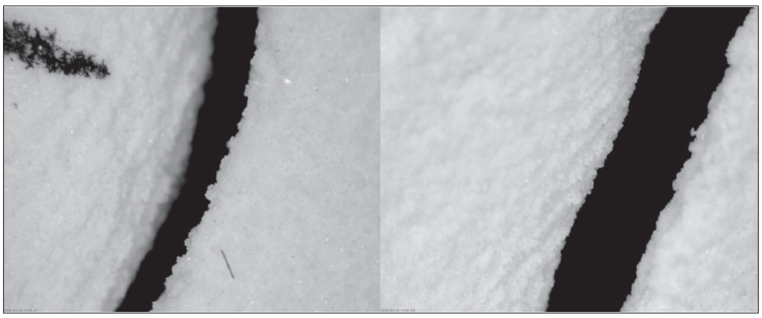

Figure 5. Edge image zoomed by microscope.

Table 1. Results of the measurements of the fissure between the defect and its implant; measurements made with the optical reflection-light microscope (Dino-Lite Digital Microscope PRO AM413T).

Measurement	Fissure width (mm)	Measurement	Fissure width (mm)	Measurement	Fissure width (mm)
1.	2.4	7.	0.2	13.	0.9
2.	1.8	8.	0.25	14.	0.65
3.	0.6	9.	0.4	15.	1.8
4.	0.6	10.	0.65	16.	0.15
5.	0.45	11.	0	17.	0.1
6.	0.2	12.	0.7	18.	1.0

The width of the fissure represents the failure in prosthesis adjustment. The maximal width of the fissure amounted to 1.8 mm, and the minimal: 0 mm. Mean width of the fissure, i.e. mean error, was approx. 0.714 mm; standard deviation 0.663 mm.

Discussion

The issue of medical model construction is more and more frequently touched upon in the current literature [5–12]. However, the majority of the described cases focus on the method of physical model construction, which may be then used for the purposes of surgery planning, creation of a biocompatible prostheses, and performance of surgery with the use of that prosthesis. Such a physical model of bone defect is then the only basis – template for a future implant. That is why there appears a need for a development of a method which would evaluate the accuracy of the adjustment of those two elements. The analysed problem results from the accepted technological assumptions of bone prosthesis creation.

Normally, the surgical procedures are performed with the use of prefabricated prostheses of standard dimensions and curvatures, which are then adjusted during the procedure [7]. This technology makes it impossible to adjust two elements precisely, especially when the geometry of the defect has a difficult shape.

When analysing the accuracy of the aforementioned adjustments, we should also take into consideration the method of fixation. The project of prosthesis presupposed implant fixation along one of the chosen axes, against the surface of prosthetic element. The analysis of edge collision based on that ideal presupposition. In practice, one should expect difficulties in prosthesis fixation, which may result from the presence of edge fragments that collide with a complicated lateral surface of the defect. That is why, when projecting the model, we should take into consideration the degree of complexity of the lateral surface and increase the free space within the fissure in the numerical model, and apply at least the conical analysis of collision of the adjusted surfaces. Lateral inner surface of the prosthesis edge should undergo some additional phasing, to make its fixation easier. Phasing degree depends on the complexity of the inner surface outline of the prosthesis.

Another problem is sharp edges of the outer surface outline. In the numerical model, the sharpness of those edges is the result of a precise adjustment of the outer surface of the defect and the prosthesis (switch between the surfaces, along the tangent). The sharpness becomes a major problem in the physical model. This results from the absolute minimal value of the layer that can be produced with a given method of rapid prototyping. In most cases this value does not exceed 0.1 mm [8,9]. Structures of a lesser value are not created.

The next problem connected with sharp edges is the physical properties of the material that the implant is made of. In fragile and brittle materials the edges may become damaged when we try to precisely adjust two very complex lateral surfaces of the prosthesis and bone defect. That is why, when choosing the RP method, it is necessary to consider the type of material applied and thus the method of edge protection (e.g. by making the edges more rounded and blunt). In most cases, the satisfactory aesthetic effect is obtained, even with the edges being 1 mm thick. Such an inaccuracy will be nearly invisible due to the prosthesis location and its coverage by skin and hair. That is why, due to the difficulties with prosthesis fixation, it is necessary to leave a larger fissure.

Easier fixation and an optimal adjustment significantly shorten the time of the procedure. An ideal situation would be such a preparation of the procedure that would not require the surgeon to perform any supplementary activities apart from the standard medical procedures; he would then focus on implementing the optimally adjusted implant of the bone defect. To obtain this aim, it is necessary to solve a whole range of problems connected with the models and the technology itself. As already mentioned above, every technology requires consideration of different modeling conditions. They include i.a. the accuracy of a given method, applied materials, dimensional and technological limitations. When projecting the model with the use of a given technology, it is necessary to take into consideration the differences in performance accuracy, depending on the machine used (although they are all of the same technology).

The advantage of the applied method of numerical modeling is its high effectiveness. It allows for a fast and easy deduction of the defect area from the model of the undamaged part of the cranium, reflected symmetrically against the medial axis of the body ('mirror-reflection'). This method cannot be used for extensive, asymmetrical damages.

Conclusions

The accuracy of the 3DP technique is sufficient to create medical models in every field of medicine.

Models created with the RP (3DP) method may be then used to form implants made of biocompatible materials, e.g. with vacuum casting method.

The application of the suggested method may shorten the preoperative time, as well as the time of the surgical procedure itself.

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