CRANIOPLASTY: REVIEW OF METHODS AND NEW TECHNOLOGIES IN CREATING IMPLANTS. CURRENT STATE OF THE PROBLEM

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Despite the lack of uniform statistical data on the number of patients with skull bone defects of various etiologies, the issue of reconstructive neurosurgical operations remains relevant. The presence of a skull bone defect not only leads to cosmetic imperfections and related psychological problems, but can also be the cause of neurological functional disorders. The purpose of this review was to analyze modern methods and materials used in reconstructive neurosurgical interventions. An analysis of modern domestic and foreign literature devoted to cranioplasty was conducted. The main materials used to close skull bone defects are covered, and methods for manufacturing implants are considered. Modern trends in the production of individual products used in reconstructive neurosurgery are presented.

Key words: reconstructive neurosurgery; skull bone defects; individual implants; three-dimensional printing.

Operations to close cranial bone defects have a history of thousands of years. There is evidence of cranioplasty being performed 7000 years BC [1]. This type of surgical intervention was practiced by representatives of various ancient civilizations: the Incas, the Britons, the tribes of North Africa, and the Polynesians. Archaeological finds indicate operations performed by the Peruvians

using one-millimeter gold plates from 2000 BC [2]. There is evidence of successful trepanations among representatives of ancient civilizations that inhabited the territory of modern Russia between the 5th and 3rd centuries BC. During archaeological excavations in the Altai Republic, three skulls of the Pazyryk culture were discovered that had non-mortem artificial bone defects in different parts of the cranial vault [3].

The success of such operations depends not only on the skill of the surgeon, but also on the materials used to close the defect. At each stage of the development of civilizations and technologies, the search for and improvement of materials used in medicine does not cease. The entire variety of materials for cranioplasty can be divided into two fundamental categories: own and foreign. The medical community is unanimous in the opinion that own tissues are the best material for performing various reconstructive interventions, therefore, the most careful preservation of bone fragments during the primary operation is the most important principle of surgery. This approach is the "gold standard" of craniocerebral trauma; in such cases, it is advisable not to remove bone fragments, but to perform primary cranioplasty with own fragments of the broken bone using bone sutures, cranial fixators and miniplates [4].

During cranioplasty, the patient's own flaps can be obtained by splitting the bones of the cranial vault of the adjacent areas or by implanting the patient's own bone flap, previously preserved during craniectomy. The negative aspects of this method are: lysis of bone fragments - according to various authors, reaches 20-50% [5-8]; infectious complications, which in some series [9] reached 25.9%. In addition, the use of split flaps is impossible in case of complex, giant and cosmetically significant defects. The production of autologous material is also possible from fragments of the rib or ilium. These implants are associated with an even greater risk of resorption due to a different path of implantation in the embryonic period than the cranial vault bones, the occurrence of a cosmetic defect at the sites of their collection, and the difficulty of forming an implant that corresponds in shape to the lost bone structures [4], which is why this approach is not used in modern neurosurgery.

The category of foreign materials can be divided into groups: allo- and xenografts; the former (processed cadaveric bone) are not currently used due to a number of reasons: a large number of infectious complications, a high frequency of flap lysis,

legal difficulties in obtaining the material, the risk of transmitting specific infections. The second group is the most in demand in neurosurgical practice, it is represented by a wide range of different materials: metals, polymeric materials, hydroxyapatite, ceramics, woven synthetic fiber.

The most widely used implants in practice are metal and polymer ones [4, 5, 10]. After a long history of using various metal alloys in reconstructive neurosurgery [11], to date, there remains only one undisputed leader - titanium - a durable, lightweight, non-corrosive biocompatible metal that demonstrates minimal infectious complications compared to other metal implants [1, 2, 9, 11].

The most frequently used representatives of the group of polymeric materials are: polymethyl methacrylate (PMMA), polyetheretherketone (PEEK), hydroxyapatite (HA), as well as the domestic “Repiren” [12, 13], less commonly used are synthetic woven fiber [14] and polyetherketoneketone (PEKK), which is little known in the Russian Federation and has appeared relatively recently.

The main reasons for performing craniectomies are traumatic brain injury, ischemic and hemorrhagic stroke, surgical interventions for fibrous dysplasia and various tumors. In the course of the conducted analysis of literature and Internet resources, we did not find accurate statistics on the number of patients with skull bone defects in the Russian Federation, it is also worth noting that similar official statistics were not found for other countries. This circumstance is explained by the complexity of accounting for such patients, the lack of a single electronic database. S. Yadla et al. [15] in the course of a systematized analysis of literary sources summarized the reasons for performing craniectomies in 2254 patients and distributed them depending on the pathology. Trauma accounted for 37.2%, vascular pathology (strokes, ruptured aneurysms) - 31.7%; craniectomies for tumors were performed in 11.2%. due to congenital pathology - in 5.7%; removal of skull bone fragments associated with infection was performed in 5.5% of cases. In 8.7%, the reason for performing craniectomies was associated with other causes (deformities associated with radiation exposure, intraoperative bleeding, pseudotumors, arachnoid cysts). According to the randomized controlled multicenter study ASTI No. 2612000353897 [16], the distribution of patients with skull bone defects was as follows: the share of consequences of TBI accounted for 67%, the consequences of decompressive operations for strokes: 16% - ischemic and 22% - hemorrhagic. The share of interventions in patients with tumors was 3%. In the study of H. Joswig et al. presented the following distribution of patients who underwent cranioplasty: 52.4% - consequences of head injuries, subarachnoid hemorrhage - 13.6%, ischemic stroke - 6.8%, intracerebral hemorrhage - 5.8%, others - 21.4%. [17]. It is worth noting that the presented data do not reflect the actual distribution of pathology by nosology in the population, although the fact that traumatic brain injury occupies a leading position, in turn, is not in doubt.

Previously, it was believed that reconstructive neurosurgical operations are aimed only at closing the defect for protective and aesthetic reasons, but recent studies have demonstrated improved cerebrospinal fluid circulation, normalization of intracranial and cerebral perfusion pressure, and improved cognitive functions after cranioplasties [18-23]; and, despite this, indications for surgical interventions have not yet been clearly defined [5]. As a rule, surgeons are guided by the clinical picture and complaints indicating the presence of trepanned syndrome, the localization of the defect and its cosmetic significance, as well as the size of the defect itself. As for the latter, the issue of the need to close small defects (up to 10 cm2) in the absence of complaints, cosmetic significance, and any clinical picture associated with the defect is still debatable.

After conducting the necessary examinations, determining the indications for surgery and making a decision to perform cranioplasty, surgeons are faced with the question of choosing the method and the optimal material for this intervention. Above, we examined the main groups of materials, analyzed the literature and our own experience, and came to the conclusion that the most frequently used implants in Russia are titanium, PMMA and PEEK [24-27].

Methods of cranioplasty can be divided into two main groups: using individual, prefabricated implants and using standard titanium meshes - blanks or polymer mixtures that are modeled and formed directly during the surgical intervention. The use of the latter increases the duration of the surgical intervention compared to prefabricated products, since the surgeon needs time to give the implant the necessary shape and curvature. A number of authors suggest using intraoperative navigation to verify the required curvature of the implant in order to improve aesthetic characteristics [4, 5], but this technique also increases the duration of the operation. The use of individual products eliminates time costs, which simplifies and speeds up the surgeon's work.

A pioneer in the direction of creating individual implants in Russia is Academician of the Russian Academy of Sciences, Doctor of Medical Sciences, Professor A.A. Potapov [5, 25-27]. The technology consists of creating implants based on a digital model of the skull of a patient with a defect(s) of the cranial bones and the subsequent use of stereolithographic anatomical models of the skull and press molds. An individual implant is obtained by casting polymethyl methacrylate into the obtained press molds; after hardening and comparison with the defect area on the stereolithographic model, the implant is sterilized and ready for surgical use.

Currently, the production of individual implants is more widespread in specialized medical industry enterprises; the products are delivered to the clinic and are ready for implantation after sterilization. There are both foreign and domestic companies on the market that work in this area; already illuminated polymers (PMMA, PEEK, PEKK) and titanium meshes are used as source materials. The production process is quite similar to that described above. At the first stage, a patient with a cranial bone defect undergoes a multislice computed tomography of the head. The study results in layered sections of the skull, which are exported as a series of digital images in DICOM format to a program for constructing a three-dimensional model. At the second stage, a volumetric polygonal model of the patient's skull is created using specialized software. Then, a virtual implant is created by a three-dimensional modeling operator to close the existing defect in the patient's cranial bones. At the third stage, the physical creation of the implant is carried out, which can be carried out in various ways: using dense silicone molds into which the polymer material is cast; using three-dimensional milling machines, which grind the polymer blank layer by layer, ultimately obtaining the desired product. When creating individual implants from a titanium mesh, a sheet of perforated titanium alloy is used, which is formed according to a three-dimensional anatomical model of the patient's skull, manufactured on a scale of 1: 1 on a three-dimensional printer; this approach is used when creating individual titanium implants of domestic production.

A considerable number of researchers speak out in favor of using individual implants. Thus, F. Schwarz et al. [28] report unsatisfactory cosmetic results of reconstructive interventions for large skull defects when “hand-made” implants are used to close them – those made from polymeric materials directly during the surgical intervention.

Eolchiyan S.A. [24] points out that the use of individual implants manufactured using CAD/CAM technologies from titanium and PEEK-Optima material demonstrates their undeniable advantages, which include high precision, reduced trauma, reduced duration of surgery and, ultimately, the achievement of a predictable, stable functional cosmetic result.

In the study by M. Cabraja et al. [29], it was demonstrated that cranioplasty using CAD/CAM developed individual titanium implants is appropriate for any bone defects, regardless of size and complexity, demonstrates a minimal percentage of complications and does not interfere with further control tomographic studies. Titanium implants are the material of choice for secondary cranioplasties in patients with the consequences of decompressive trepanations after traumatic brain injuries or other urgent neurosurgical conditions.

In the work of the team of authors headed by J. Höhne [17], the results of cranioplasties performed between 2006 and 2013 using two different methods were compared: the first group (60 cases) consisted of patients who underwent interventions using implants made intraoperatively from polymethyl methacrylate (PMMA), while the second group (60 cases) used titanium meshes pre-formed according to anatomical models. The operation time in the second group was significantly lower than in the first, and patients from the second group demonstrated fewer complications and better cosmetic results.

In the study by JM Luo et al. [30], conducted between 2005 and 2011, 161 patients were divided into two groups: those using titanium mesh implants modeled during surgery (78 cases) and those using titanium mesh implants pre-modeled before surgery using CAD/CAM programs (83 cases). The authors demonstrated that the use of implants created based on a three-dimensional model of the patient's skull at the pre-operative stage reduces the duration of surgery, allows for the use of fewer screws to fix the implant, reduces the number of post-operative complications, and allows for better aesthetic results.

Kwarcinski J. et al. [31] in the course of the conducted systematic review came to the conclusion that the risk of postoperative infectious complications is significantly increased by the duration of the operation and repeated surgical interventions [32], while the comparison of implants from different materials does not allow to clearly identify the ideal raw material demonstrating minimal infectious risks. The authors also hypothesize that the structure of the implant, which promotes better integration into the surrounding tissues (porosity, roughness), can affect the reduction of postoperative trophic disorders and, as a result, the reduction in the frequency of implant infection.

Bonda DJ et al. [33] in their review indicate that the use of individual implants obtained on the basis of three-dimensional modeling and printing methods is the most obvious prospect for reconstructive neurosurgery.

DISCUSSION

Having analyzed the literature and our own experience of using various types of implants for cranioplasty, we came to the conclusion that the use of individual implants is justified in all cases of closure of skull bone defects. This point of view will certainly cause a lot of controversy, but if we consider the problem from the point of view of rational use of resources, this statement is quite justified. When using individual products, compared to standard blanks for cranioplasty, the time spent by the surgeon on forming the implant during the operation is reduced. The use of individual implants eliminates possible play and gaps between the plate and the bone, which requires fewer screws and guarantees good adhesion and fixation to the skull. After operations with standard titanium plates, cut fragments remain, which, as a rule, are not used in the future. If we analyze this circumstance on the scale of a large city, in a year we will get an impressive amount of material that is irretrievably disposed of without recycling.

The methods of creating individual implants by molding them using an anatomical model of the patient's skull and using press molds, however, are also not without drawbacks. As the surgical intervention is performed, there are products (an anatomical model of the skull, a press mold) that are no longer used and require disposal. Currently, the medical industry is actively developing the direction of three-dimensional printing, which is the most cost-effective

positions of using materials. We have considered the most common methods of additive technologies used in the Russian Federation: fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS) and direct metal laser sintering (DMLS) [34]. Thus, SLS and SLA printing are comparable in terms of the accuracy of the resulting models, while the products are superior in strength characteristics to analogs made by the FDM printing method. However, the listed methods currently do not use biocompatible raw materials approved for use in medicine and implantation, which does not allow for the immediate manufacture of the desired implant. Thus, using the specified methods, it is possible to manufacture a prototype of an implant , but to create the medical product itself, it will be necessary to either create a mold based on the prototype and then fill it with a hardening medical polymer, for example, polymethyl methacrylate, or mold the implant using the prototype as an anatomical model.

implants without any intermediate products (press molds, anatomical models) . When manufacturing individual titanium implants using this method, unsintered material can be reused after removal from the working chamber, which minimizes raw material losses.

Production is virtually waste-free, which distinguishes DMLS from subtractive technologies such as milling, and allows for the creation of several models simultaneously, limited only by the size of the working chamber [35]. Model construction takes hours, which is incomparably more profitable than the casting process, which can take up to several months, taking into account the full production cycle.

The DMLS method was chosen by us as the optimal method

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creation of individual implants for reconstructive interventions on the bones of the skull. The manufacturing process using DMLS technology differs from the one described above only in the method of direct production of the product. After creating an individual implant in a virtual environment, the third and final stage involves printing the implant from titanium (^64) powder on a 3D printer. As a double check, at the same stage we created a fragment of the patient's skull in the area of his defect using the SLS printing method from polyamide. The creation of an anatomical model allows us to verify the congruence of the resulting implant before the operation. After which the implant is sent for sterilization by autoclaving, and then the product is ready for implantation [34, 36, 37]. The production of implants using this method allows doctors themselves to participate in the development of their design: from the choice of surface texture and methods of its attachment to the creation of additional elements (stiffeners, centering guides, additional holes for drainage of the subimplantation space, additional fixation points for soft tissues, etc.).

Currently, a number of authors present their works devoted to the search for methods of creating cheap individual implants , since the average cost

The cost of similar products abroad is 3000-7000 euros, depending on the material used, and is quite high even for developed Western countries [24, 38].

Thus, in the work of Eddie TW Tan et al. [38] indicate that the creation of individual implants can be carried out by a surgeon himself, who has the skills of simple computer modeling. The authors suggest using a low-budget desktop 3D FDM printer to manufacture molds from PLA plastic, into which a biocompatible polymer is cast (the authors used Surgical Simplex P Radioopaque bonecement by Styker Corporation). Thus, the surgeon can independently manufacture the individual implant of interest to him, without resorting to anyone's help. According to the authors, the price of such implants is several times lower than industrial analogues offered in Europe and North America. According to Pham BM et al. [39], a reduction in the cost of individual implants for cranioplasty can be achieved through three-dimensional modeling of the desired product by the surgeons themselves directly in the clinic, however, the authors point out that this requires special knowledge in the field of CAD / CAM modeling. In our clinic in the period 2014-2015. a similar approach to creating individual implants was tested and compared with products obtained in specialized medical production. In our opinion, optimization of the working time of surgeons and the quality of the products obtained are priority tasks, therefore, the production of individual surgical implants should be carried out on the basis of licensed enterprises of the medical industry using specialized equipment. While the price of individual products can be reduced not by shifting the tasks of three-dimensional modeling to doctors, but by developing programs that allow modeling the desired implant in automatic or semi-automatic mode [40]. The study of biocompatible polymers (PEEK-FDM, PC-ISO, ABS-M30i,

FDM Nylon 12), already used in 3D printing for their safety as a raw material for implants. These approaches will increase the availability of medical care using individual products obtained by 3D printing.

CONCLUSIONS:

1. The use of individual implants is appropriate in neurosurgical practice for any size and location of bone defects.

2. The technology of direct laser sintering of metals is currently the optimal method for creating individual titanium implants in Russia.

Z. For wider coverage and timely provision of surgical care to patients with skull bone defects, it is necessary to create a single registry and accounting system for patients with this pathology.

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