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The Use Carbon Composite Material For Replacement of Postresection Bone Defects

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https://doi.org/10.33847/2686-8296.5.2_3

Received 06.11.2023/Accepted 13.11.2023/Published 14.12.2023

Abstract. In studying the use of various implanted materials, the authors found no case reports of carbon composite material for children in the available literature. The boundaries of carbon composite material use are not clear, and indications and contraindications for its applying are not outlined. Therefore, the authors decided to share the initial experience of its use for the replacement of post-resection bone defects for children. The paper presents the results of surgical treatment of 8-16-year-old children with extensive bone defects after resection of pathological tissue with the use of highly porous cellular carbon in isolation and in combination with autografts. During the study, children with damage to long bone segments - tibia, shoulder, and femoral were operated on. The clinical and radiation results of this study have been evaluated based on the Musculo Skeletal Tumor Society Score Scale. 100% of treated patients were rated as good for period from 7 to 12 years after surgery. There were no complications in the operated patients. Full integration of the implantable materials was observed with good clinical and radiological results.

Keywords: carbon composite material, transplantation of tissues replacing bone, autograft, allograft.

1. INTRODUCTION

The replacement of bone defects for children is very relevant and does not lose its acuteness in case of benign cystic formations or diseases. Such pathology in childhood is very common and tends to increase in frequency, second only to infectious diseases, cardiovascular diseases, respiratory diseases and diabetes mellitus [1].

Orthopedic traumatologists are actively improving both conservative and operative treatment methods using various innovations and improved transplantation materials [2]. The search for implantable materials for replacing defects after removal of tumors or tumor-like areas of altered bone continues to this day [3, 4, 5, 6]. The processes of bone reaction to the introduction of implanted materials and subsequent bone formation continue to be studied [7, 8, 9]. Much attention is paid to the use of inert materials (e.g., carbon-carbon composites), which by their physical and chemical characteristics are close to the organic structure of the human body. Research on carbon composites for the replacement of bone defects and cavities continues both in the field of implant fabrication
technologies and in improving the effectiveness of applying this material to different anatomical areas [10].

In the USSR, specialists have long been interested in alternative methods of full replacement of bone defects, in how to effectively apply the replacement of bone defects with carbon composite materials, studied how the body behaves in this case, what conditions should be provided to obtain the best result, attempts were made to improve regeneration by electrostimulation [11]. The transition to high-porosity cellular carbon-carbon materials is a natural outcome of further study of carbon composites.

The successful use of porous carbon in adult traumatology and orthopedics was the result of in-depth research and numerous studies. In clinical use, this material has proven itself well, which was sufficient reason to introduce this technology in children with a certain degree of caution and under mandatory dynamic monitoring [5, 12, 13, 14].

It is important to note that all materials other than autogenous bone are non-autogenous grafts. However, harvesting autologous bone, especially in children, is an additional operation that causes additional trauma to the child. Donor resources in childhood are limited; there is a risk of infection or even fracture in the area of autologous bone extraction, there are cosmetic disorders, there is a risk of complications in more than 15-20% of observations. This motivates specialists to search for effective bone replacement materials.

2. LITERATURE REVIEW

Recently, bio composite grafts have competed quite well with their predecessors. The use of composite materials is a whole direction in clinical traumatology [15 - 23]. In parallel with other alternative studies, the direction of using carbon materials for bone void replacement is developing [11, 12, 24]. The choice among these materials is also differentiated for different patient groups. Constructs for bone void replacement made of the carbon-carbon material "Uglekon-M" have not been used in pediatric practice due to difficulties in material remodeling [10]. At the same time, high porosity cellular carbon has become a great prospect, especially for use in the metaphyseal area to fill post-traumatic defects in adult patients [25]. We have not seen any reports on the use of such materials in pediatric practice. The advantage of implants made from this material is that its mechanical properties are close to those of native bone, the material is inert to living tissue, but no one has taken advantage of the possibility of using these already proven composite materials in children [5, 12]. Our experience with the use of highly porous honeycomb carbon material in children has demonstrated its high efficacy, with clear boundaries for the use of this material in young patients [26]. However, accumulated clinical experience has revealed additional aspects of working with carbon composites.

Both biological and purely mechanical mechanisms of survival of implants made of this material are of interest; the problems of biomechanical behavior of the bone-implant system under functional loads in the conditions of a growing organism have not been studied.

The further consequences of these materials’ use in children and the peculiarities of the implant interaction with the surrounding tissues are curious.

The main purpose of this work is to study our accumulated clinical material on the use of carbon composite material in children after resection of benign tumor masses and to discuss the revealed biomechanical aspects of its application.

3. DATA AND METHODOLOGY
In the period 2002 - 2022 were operated 12 children aged from 8 to 16 years in whom we replaced the formed bone defect with carbon composite material during surgery with removal of pathological bone in fibrous dysplasia, aneurysmal cyst, nauseous bone fibroma, solitary bone cyst. All tumors were benign, in fact the cavities were cysts with weakened structure, thinning of the compact surrounding bone. The cavities were treated with osteotomes, Folkman rongeurs and burrs, leaving visually unaltered bone tissue. Highly porous cellular carbon with a high implant porosity of 70 to 90% was used to replace the formed bone defects in all patients [26].

Tissue replacement was carried out on the clavicle, humerus, femur, tibia and calcaneus. Technically, in the vicinity of the growth zone, we tried to isolate it from the implanted material using spongy autobone, which we consider to be one of the necessary conditions for the use of composite implants. However, this was an exercise in caution in the initial application of the material. We successfully replaced the rest of the defect with carbon composite. The bone walls were preserved by working with sharp instruments or burrs "to the bloody dew" to ensure that the quality of the native bone was adequate. A combination of implant material and native autogenous bone was used in 3 patients.

Highly porous cellular carbon is itself a lightweight material, almost pure carbon. It is easy to work, can be cut with a knife and the implant can be given any shape corresponding to the formed bone defect (Fig. 1). The cellular structure of carbon facilitates its processing, promotes the integration of bone tissue into hollow cells and the porosity of the material reaches 90%.

It is understandable that the clinical application of highly porous structures required caution and a preliminary assessment of the possible biomechanical consequences of implanting this material. In 9 patients, we managed with isolated application of the carbon composite without any particular concern for bone
weakening. However, when the focus of destruction was found in the highly loaded region of the femur, we had to perform some additional studies.

In order to study the influence of the bone destruction Centre (Fig. 2) on the load-bearing capacity of the loaded skeletal segments, a spatially inhomogeneous anisotropic linear-elastic finite element model of the hip joint was constructed in collaboration with scientists from the Perm National Research Polytechnic University (Fig. 3). The model was individualised using spiral, three-plane computed tomography data and the patient's anthropometric parameters.

![Image](image.png)

**Fig. 2.** Localization of the destructive focus according to computed tomography of the hip joint of patient T., 14 years old.
Source: authors' elaboration.

The digital model is represented by femur and pelvis bones with articular cartilage. The cartilage was modelled as a homogeneous isotropic layer of complex geometric shape. In this problem formulation, the contact intercartilage interaction was not investigated. A cartilage thickness of approximately 4 mm, corresponding to the width of the radiological joint cavity, was assumed, taking into account both contacting cartilage layers. The finite element method was used to calculate the stress-strain state of the bone tissue.
Fig. 3. Computer model of the hip joint. Arrows indicate functional loads and kinematic boundary conditions. Source: authors’elaboration.

The results of the stress-strain state calculation of bone tissue are shown in Fig. 4.

Fig. 4. Stress (A) and strain (B) fields in bone tissue in the presence of a cyst in the femoral metadiaphyseal zone. Source: authors’elaboration.

Obviously, the presence of the cavity leads to a redistribution of stresses in the bone tissue around the defect and creates conditions for the formation of dystrophic...
changes at the base of the femoral neck. In such a case, Adams' arch, the vertebral area above the cavity and the destructive area of the cyst itself become the zone of potential risk of fracture. The walls of the cyst, which are in a critical state due to overloading of the cortical layer, are at greater risk of destruction the larger the cyst itself is. As a result, the risk of pathological fracture increases significantly, which becomes a serious reason to decide on the need for additional measures to stabilise the segment.

This clinical case clearly demonstrates that computer modelling of the development of possible complications depending on the size and location of the cyst allows us to weigh the risks of conservative treatment, determine the need for additional osteosynthesis, and formulate recommendations on the sequence and characteristics of rehabilitation.

In this patient, the analysis of the results of the calculations allowed us to formulate the following statements: critical areas of overload are an indication for surgical correction; in the area of Adams' arch, at the base of the femoral neck and at the level of the cyst itself, foci of bone tissue weakness are created, predisposing to pathological fractures. This allowed the surgeon to decide preoperatively on the need for additional fixation and to select a fixator option.

The ISOLS system proposed by the International Society for Organ Preserving Surgery was used to assess long-term outcomes. The system used also included all similar significant clinical features of the MSTS (Musculo Skeletal Tumor Society Score). In the scoring systems, six clinically relevant parameters were scored on a 5-point scale, and the clinical outcome was represented by the sum of the scores. An excellent outcome ranged from 23 to 30 points, a good outcome from 15 to 22 good points, a satisfactory outcome from 8 to 14 points, and an unsatisfactory outcome from 0 to 7 points. In drawing conclusions, we categorised excellent and good outcomes as 'good' because the differences in outcomes were not significant. Treatment efficacy was assessed as a percentage, reflecting the difference between the increase in score after treatment compared to the patient's baseline score, which is conventionally taken to be 100%. Thus, 30% efficacy means that the increase in postoperative score was 30% of the patient's preoperative baseline score. All clinical data had radiological verification, which was important to assess the integration of the implanted materials into the bone. [14].

4. RESULTS

The replacement of bone tissue defects was performed exclusively using carbon-carbon composite implantable material consisting exclusively of bioinert carbon with porosity of 70-90% in 9 patients, and in combination with autografts in case of extensive defects in 3 patients. In the latter patients the material was used in order to reduce the amount of autograft used (2 patients), and in 1 patient the carbon composite was applied in the metaphyseal zone of the tibia in combination with spongy autograft for isolation from the growth zone. The application of the material did not imply further axial load on the replacement material, so 2/3 of the patients had temporary limitation of the total load on the limb for 4-6 weeks, in the rest there was no such necessity, in our opinion.

We believe that the situations in which combined plasty of the bone defect formed after removal of a bony benign tumor was performed were very favorable. The limited possibilities of graft taking, the desire to reduce the graft quantity were one of the reasons for the additional use of cellular carbon-carbon composite. In young children the wing of the iliac bone can be very thin additional traumatization is undesirable. We have always predicted with high probability a positive outcome of such combined plasty, which has always been justified. The walled location of such
defects, initially with a preference for the metaphyseal region, was considered by us to be favorable conditions for replacement of the defect with carbon material. This is well illustrated by the presented clinical case.

Clinical example. Patient K., 10 years old. A solitary bone cyst of the metaphyseal region of the femur was detected; he was referred because of pain, lameness, and contracture in the hip joint (Fig. 5).

![Fig. 5. Patient K., 10 years old. Radiographs of a solitary cyst in the thigh region, the edges of the cyst are sclerosed, traces of multichambered structure. Source: authors’ photography.](image)

The patient underwent combined autoplasty of the defect in combination with carbon-carbon composite (2/3 of the total volume), the defect was replaced with bone and modeled carbon pieces, the original size of the defect after cyst removal was 5x3x3 cm. A fragment of the bone cap on the periosteum was cut out at the access and used at the end of the surgical intervention to close the defect by subcutaneous sutures (Fig. 6).

![Fig. 6. The same patient K., intraoperative view of the replaced bone defect and the moment of cyst replacement with carbon cellular material. Source: authors’ photography.](image)
Wound healing by primary tension. Immobilization was not performed. After wound healing, the patient moved for 3 weeks on crutches, then full load was allowed. Already six months after the operation, the restoration of the structure, complete bone tissue remodeling was noted, there was no recurrence. Observation for more than 12 years. Full recovery of the hip movement amplitude 4 months after surgery, leg length is the same, the supporting function of the operated limb is not disturbed.

Whenever possible, we used at least some of the usable cortical wall in the intervention after appropriate treatment for implant closure (Fig. 7).

![Fig. 7. Patient P. 8 years old. A part of the suitable wall of the diaphyseal bone section was used to close the implanted block. Source: [31].](image)

The maximum length of the defect replacement was noted on the tibia at the removal of the foci of fibrous dysplasia and amounted to 11 cm (Fig.8).

![Fig. 8. Patient T. 12 years old. Source: [31].](image)

Fig. 8 illustrates treatment and replacement process of the humerus defect with carbon composite. The bone wall is not suitable for plasty. The carbon material is covered with periosteum.

In principle, replacement with carbon composite did not differ from other methods; we used variants of closing the external wall with a preserved part of the cortical wall or simply covered the material with periosteum. No significant differences in the application of these methods of placement and fixation of the material were revealed. The whole material of isolated application of carbon composite amounted to 9 observations.

A few words should be said about the use of combined bone grafting with carbon composite material when it is necessary to use an additional resource in the
form of the patient’s own bone. This is, on the one hand, a question of the volume of the bone lesion, and on the other hand, an anatomical need due to the proximity of the epimetaephyseal bone growth zone. In most observations, the cystic formation did not sprout through the growth zone. However, with the proximity of the growth zones, we believed that in any case, the physeal plate should be isolated from the affected bone and from the implant with autologous bone.

When bone autografts were taken in the case of combined interventions, no complications were observed at the site of donor bone harvesting, although this manipulation involves known clinical risks [27].

None of our operated patients had specific complications when using these materials, complete reconstruction of grafts occurred within 6 months to 1 year. There were no recurrences in the future, the follow-up period was from 10 to 20 years, there was no need in repeated surgeries.

The clinical results, performed as an additional study, fully coincided with the applied grading systems according to the MSTS schemes. In general, the results in 100% of treated patients were evaluated as good. The treatment efficiency according to the ISOLS system was +56.8% after treatment in the group after plasty with carbon composite. These data are not inferior to the effectiveness of treatment with the use of other artificial materials and are close to the results with the isolated use of autologous bone, which is recognized by all authors as the most physiologically justified [3, 5, 9, 26].

The use of a mathematical model to be able to predict the behavior of the implanted carbon material was a great help in making the decision to perform such an operation. We had no literature data on the use of composite carbon materials in children, so any clue in this regard was very valuable to us. The mathematical model gave an idea of the loading of the implant itself, its surrounding zones, allowed us to predict biologically favorable conditions and assess the risks of pathological fractures, helped in choosing the optimal accesses and their sizes.

The aim of our study was to present the long-term results of treatment of children with the use of highly porous cellular carbon for the replacement of tumor and tumor-like bone defects of the type of extensive cysts in children after resection of pathologically altered tissues. The nature of the process was clarified by histologic examination. The use of highly porous cellular carbon or other composite carbon materials in pediatric traumatology and orthopedics is not covered in the literature available to us. Carbon materials in the form of nanostructured carbon implants were used in foot surgeries, but the authors did not obtain the expected formation of a true bone-carbon block [28]. Maybe the loaded bone area, or the structural features of the implanted material did not produce the expected results. The results, however, are regarded as good; bone fouling of sufficiently inert implants was achieved.

The porosity of the materials we used is 70-90% or more, so we did not count on their support and relied on the biocompatibility of the carbon itself. The successful use of this material in adult practice gave us confidence in the possibility of its use in children. Nevertheless, we were quite cautious about this material at the beginning of its clinical use, and limited its use to extensive bone defects in the metaphyseal, metadiaphyseal region and at the level of diaphyses of long bones.

The peculiarities of the surgical access without weakening the supporting, intact compact part of the bone ensured its sufficient strength after surgery. We believe that clinical results allow us to assert the osteoconductive effect due to the high porosity of the material, its inertness, and biocompatibility, which demonstrated its use at the level of bone marrow and spongy areas of the metaphysis. The usual localization was metaphyseal, metadiaphyseal part, especially in marginal lesions, and bone marrow cavity at the level of diaphysis.
the case of a limited cortical defect, we relied on subsequent remodeling of the periosteum over the implanted material, which is what we actually observed.

In all cases where the material was used, the patient and their representatives were informed, justification was provided, and consent was obtained in all cases for the use of this still uncommon material.

The achieved clinical results indicate the effectiveness of replacement of extensive diaphyseal, metaphyseal or metadiaphyseal bone defects with carbon composite material. We have used autografts in addition to the above implants in case of significant cavity size, when additional stimuli of regeneration are required, when there are nearby areas of bone tissue with critical nutritional conditions along the lines of force loads or in areas with reduced blood supply, in the vicinity of physeal zones, when there is a threat to weaken the bone tissue to a critical state. We remain convinced that the growth zone should be isolated by autografts from contact with the implanted material.

In general, the use of carbon composites for bone void fillers is justified. Highly porous carbon, by virtue of its porous structure, is thought to be an osteoconductive material that ensures the ingrowth of its own bone with true osteointegration. The "filling" of porous bone areas with blood elements is, in our opinion, the basis of such structural reorganisation. Comparison with other authors' data suggests that the attribution of osteoinductive and osteoconductive properties to composite materials by other authors is more wishful thinking than reality. The question remains open. In our opinion, the use of combined bone autograft and carbon composite material in the replacement of extensive bone defects offers the opportunity to exploit all these positive properties of grafts. Other possibilities for the combined use of this composite material need to be investigated in both children and adults. Highly porous cellular carbon consists almost entirely of carbon, which is inert to the human body. This makes it safe to use. The material is easy to work with, can be cut with a knife and the implant can be shaped to suit the bone defect. The porosity of the material reaches 90% and more. Early studies have also shown that bone elements grow into the implant cavities, and the material does not cause autoimmune or allergic reactions, which is also confirmed by our experience.

It is difficult to draw conclusions from a single observation with the treatment of recurrences with fibrous dysplasia, but it can be assumed that in some cases with extensive defects allografts may be ineffective, insufficiently effective and prone to recurrence. And in this case the use of highly porous carbon may be the method of choice.

Further wider application of this material for the replacement of lower limb defects is associated with certain difficulties and requires solving a number of engineering and clinical problems. First of all, we should pay attention to the fact that the segments of the lower limb are subjected to significant functional loads, which can cause implant failure. That is why it is very important to estimate the biomechanical consequences of the choice of the material, size and shape of the implant, the volume and character of the intervention already at the preoperative stage. A promising way to solve this problem, in our opinion, is the use of computer modeling methods, because with the help of a digital twin of the limb segment of interest it is possible to conduct a computational experiment and calculate the fields of stresses and deformations occurring in the bone. The use of digital twins (computer models) to solve clinical problems (calculation of biomechanical consequences of the choice of implanted material) was demonstrated by us in [29, 30].

It should also be emphasised that the mechanical properties of carbon composite materials can vary over a wide, clinically significant range, and the technology of manufacturing implants (grafts) from this material allows the
production of samples with a pre-designed, heterogeneous distribution of mechanical properties. Determination of individual loads on lower limb segments and engineering calculations will allow to avoid possible clinical complications associated with failure of the implanted construct during bone grafting of limb segments. The above allows us to consider this material as promising from the point of view of the manufacture of personalised implants, and the application of this technology (bone grafting with carbon-carbon composites) of different porosity and strength can be generalised to the lower extremities after appropriate engineering calculations. In general, biomechanical problems should be solved taking into account the favourable biological compatibility of the proposed carbon material, and the place, favourable conditions and limitations of its application should be clearly defined.

5. CONCLUSION

The use of carbon composite material for the replacement of post-resection tumor and tumor-like bone defects is considered highly effective in children aged 8 to 16 years. The efficiency of treatment according to the ISOLS system was +56.8% after plasty using carbon composite, which was confirmed by radiation studies and improvement of quality of life. In 10-20 years after the operation, 100% of the children had good results, and there were no complications when using these implants alone or in combination. When comparing artificial plastic materials, we should recognise the most promising - fine-porous variants, in particular highly porous cellular carbon, due to its inertness and high affinity to living tissues. The biomechanical properties of the implanted material need to be further studied using computerised digital duplicates. The results of the computer modelling allow the surgeon to assess the risks of continuing with conservative treatment, to decide on the need for additional fixation and to select a fixator variant in the preoperative phase. The digital twin is an addition to the surgeon's arsenal of tools used to assess the influence of the shape and location of the defect on the risk of possible bone separation. The use of digital tools makes it possible to quantify high-risk clinical situations and justify the need to remove the pathological focus and restore the bone structure. Finally, the proposed approach will allow a wider application of high porosity carbon implants and improve their vitalisation conditions. In conclusion, the method developed and applied in the clinic for the treatment of post-resection bone defects using carbon composites is effective and promising.

ACKNOWLEDGMENTS

This research was funded by Ministry of science and higher education of the Russian Federation (Project № FSNM- 2023-0003).

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©ICS. Journal of Digital Science, ISSN 2686-8296, Vol.5, Iss. 2, December 2023


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Printed online from the original layout under the imprint at:
1, Vlachou, Nicosia, The Republic of Cyprus

©ICS. Journal of Digital Science, ISSN 2686-8296, Vol.5, Iss. 2, December 2023