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3D MODEL SIMULATION IN PREOPERATIVE PLANNING OF COMPLEX AND REVISION HIP REPLACEMENT

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Abstract

Complex and revision hip arthroplasty has remained one of the most discussed orthopedic topics in recent years. With the advancement of printing technologies 3D preoperative planning and live model simulation provides us with "hands on" procedures without any risk for the patient. Modern computer technologies present the possibility for preoperative planning of Total Hip Arthroplasty (THA) in digital environment. 3D printing of anatomical models in real size allows accurate assessment of the pathological deviations of the anatomy, precise preoperative planning of the reconstruction and simulation of the operative intervention ex-vivo. We present a series of 3D simulations for planning hip replacement, illustrating the technique, discussing its advantages and disadvantages, in complex primary and revision hip arthroplasty. In the complex and revision surgery of the hip joint, a correct assessment of bone defects is mandatory. Reconstructing the biomechanical parameters – centre of rotation, femoral offset and leg length discrepancy, is also of great significance. The 3D reconstruction with biomodel simulations offers exceptional accuracy in this respect. The method can be an excellent tool for education of surgeons in training and residents.

Key words: 3D printing, revision hip arthroplasty, preoperative planning, computer technologies

Introduction. Preoperative planning is an important part of the reconstructive surgery of the hip joint. Its significance was first discussed in the 60s

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of the past century by Charnley [1], who underlined the need for accurate determination of the type and size of components, alignment of the length of limbs, and achievement of correct orientation and position of the components of the hip joint prosthesis. Correct reconstruction will provide long-term survival of the hip prosthesis, minimization of the postoperative complications, anatomical recovery of the hip biomechanics, and ensuring better function of the artificial hip joint. Initially, the preoperative planning was performed by conventional method, using native X-rays and models of different designs of the components, which were superimposed on the X-ray picture [2–4]. The introduction and development of computer technologies offer planning in digital environment with the use of specialized software. Some authors use programs for technical drawing in the architecture and industry, based on CAD-software [2]. Specialized systems developed for orthopedic practice occurred subsequently.

Digital techniques in the primary arthroplasty of the hip joint are well studied in the literature [2, 5]. We found less information regarding the complex and revision joint arthroplasty, particularly the computer technologies for preoperative planning and intraoperative assistance. Complex joint arthroplasty is defined as hip replacement in patients with severe bone and/or soft tissue impairment in the region of the affected hip joint. Various etiological factors are responsible for such defects: congenital hip dysplasia, protrusion of acetabulum, condition after acetabular and femoral fractures, infection, skeletal dysplasias, etc. [6]. Revision arthroplasty is required in a series of complications of already implanted primary joint arthroplasty [3, 7]. In these cases besides the plan of reconstruction, a good management and logistics are necessary, because the revision surgery is associated with multiple risks – increased blood loss, increased risk of infections, joint dislocations, loosening, management of the patient's comorbidity, etc. [8–10]. The most frequent reasons leading to revision of the hip joint are aseptic loosening of the components of the hip joint with/without bone loss, periprosthetic infections, periprosthetic fractures, joint dislocation, fracture of the acetabular or femoral components and some other conditions [10, 11]. As mentioned above, restoring biomechanics of the joint is the key for long-term survival and good function of the endoprosthesis. But when there is severe bone loss, biomechanical parameters could hardly be reconstructed. The bone defects are one of the most difficult problems in hip joint reconstruction, and are a challenge for every surgeon [12].

The revolution in computer technologies, especially in recent years, provides increasingly more precise instruments and methods with application in the surgery of the hip joint. In 1988, the first 3D printer of Charles Hull was patented, and the technology was described as stereolithography. With its development this technology is used in medicine and biology for different purposes, and in orthopedics and traumatology, respectively [13, 14]. In hip joint arthroplasty, 3D printing can be reviewed in three directions: printing of anatomical models for analysis and preoperative planning, creating patient-specific set of instruments,

construction of individual implants and components [14]. The technique uses computed tomographical image, which is processed, and the desired object is printed from it. Creating anatomical biomodels in real size gives a possibility for accurate assessment of the pathological deviations from the anatomy [15], precise preoperative planning of the reconstruction itself and simulation of the operative intervention ex-vivo [14, 16–18]. Several publications are found in the literature concerning this question, but up to this moment the technique is still in development [13, 14, 16, 17].

Material and methods. We present a series of 25 patients operated in the Clinic of Orthopedics and Traumatology at University Hospital "Tsaritsa Yoanna – ISUL" by one surgeon. In two cases primary complex hip arthroplasty was performed, and in other 23 – revision hip arthroplasty. Patients were with the following pathology: 13 cases (52%) with aseptic loosening; 11 cases with periprosthetic joint infection; one case (4%) with failure of acetabular fracture fixation. The mean age was 64.9 years (38–81 years). Thirteen (52%) were females and 12 (48%) were males. Besides the standard X-ray, lateral radiography of pelvis and lateral radiography of the affected hip joint, computed tomography (CT) of pelvis and proximal femurs were performed. Thorough analysis of the pathology and preoperative plan were made. 3D anatomical models were reconstructed as described below.

CT-examination with a protocol for decrease of the artefacts was used. These artefacts were caused by the present metal parts of the previously implanted prostheses. This modification includes reduction of the voltage and magnitude of current, provided by one revolution of the X-ray tube – up to 120 KV and 100–200 mAs [19]. The thickness of the CT sections is 1 mm or less. The volume of the scanned area included the pelvis and proximal femurs as far distally as the end of the implant. The obtained image is in DICOM format. Presence of significant artefacts in the tomographic image, as well as the use of thicker sections, results in a model with poor quality, which does not provide significant benefit for the preoperative reconstructive plan.

The next step of the technique was converting of the DICOM-file by means of program for imaging processing (IPS – Imaging Processing Software). We used the program 3D slicer 4.9.2 and PreForm 3D. We then applied volume rendering in order to visualize the model in real size. The structure of interest was then cropped. Additional thresholding was used for further differentiation of the bone structure from the soft tissues surrounding it. The selected object was further manipulated for minimizing the model defects based on the intensity. With the threshold effect we could also remove the implants from the bone. Then we selected the "make model effect" to create a printable model. The achieved image was recorded in .stl format (stereolitographic format), suitable for 3D printing. The stl-format contained information for the sizes, form, density, and texture of the three-dimensional object, which is to be prepared by the 3D printer [17, 18].

Additionally, we could use the achieved model for virtual simulation and assessment. We were able to create hemispheres with different dimensions and could choose the correct size of the acetabular cup. X-ray view of the virtual simulation gave us good visualization for the implant fixation and the need of placing implant with larger size (Fig. 1). Additional structural augments can be planned (Fig. 2).

For the printing we used the Preform 3.22.1 program. By securing the model with additional support structures we ensured safe printing process. For precise prints we used a layer thickness of 0.100 mm and white, fine detail matte white finish.

The last step was the printing which was performed with a suitable material (in our case – polymer). The time necessary for the creation of anatomical model was over 24 hours.

The obtained anatomical model reproduced in real size and in real space the anatomy and pathology of the respective patient, while it gives a better notion of the surgeon for the condition and peculiarities of the concrete structure. The defects in the bone could easily be specified and classified accurately according to the classifications generally accepted in practice. In our study we used Paprosky classification [15]. The so-called surgical simulation follows – preparation of the model with a set of instruments, used for the concrete reconstruction. The ex-vivo preparation of acetabulum was performed with increasing sizes of reamers by the surgeon, thus creating implantation surface of the model. The techniques and the required implants for reconstruction were analyzed, and sample implants were tested. The following implants were taken into consideration – different sizes of acetabular capsules, semilunar or supporting augments, antiprotrusion cages and also the possible need for bone substitutes and allografts.

Results. We simulated all 25 surgeries with the technique as described. Computed Tomography of pelvis was performed, based on which anatomical model was prepared, followed by virtual simulation. The assessment of the Paprosky classification [15], compared with determination of bone defect by X-ray, and planned size of the components were presented in the following results, as well as postoperative components that were implanted.

Forty-four percent of the cases (N:11) were with difference of bone loss in comparison with classifying it by conventional X-ray. Some not so severe or hidden by the implant bone defects could be seen only when a 3D simulation is created. With the 3D planning technique we estimated 15 cases with severe bone defects (IIIa, IIIb, classified by Paprosky) (Fig. 3). In six of them structural augment was planned and in three of them antiprotrusion cage was considered a primary reconstruction solution. We must underline that in each case we made at least two templates (including different designs and sizes of capsules, additional augmentation or cage usage) (Fig. 4). In ten cases acetabular bone grafting was planned but intraoperatively was applied in five arthroplasties.

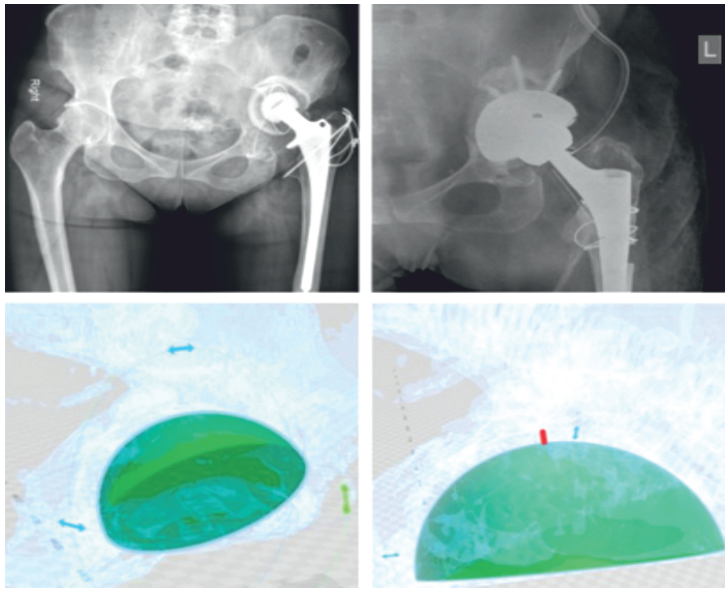


Fig. 1. 3D simulation of acetabular template and the X-ray visualization of the model. Slightly undersizing could be noticed in the last picture

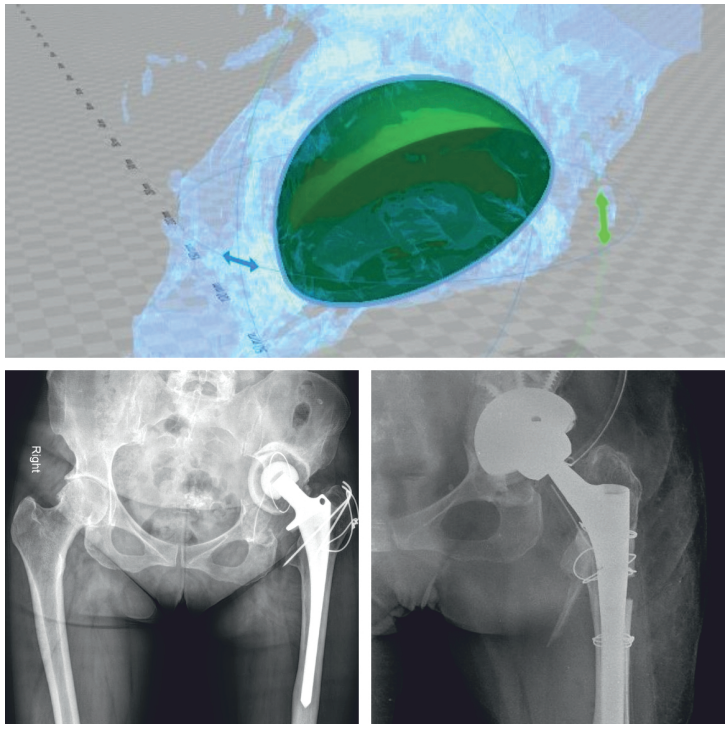


Fig. 2. Structural augment planned with the simulation

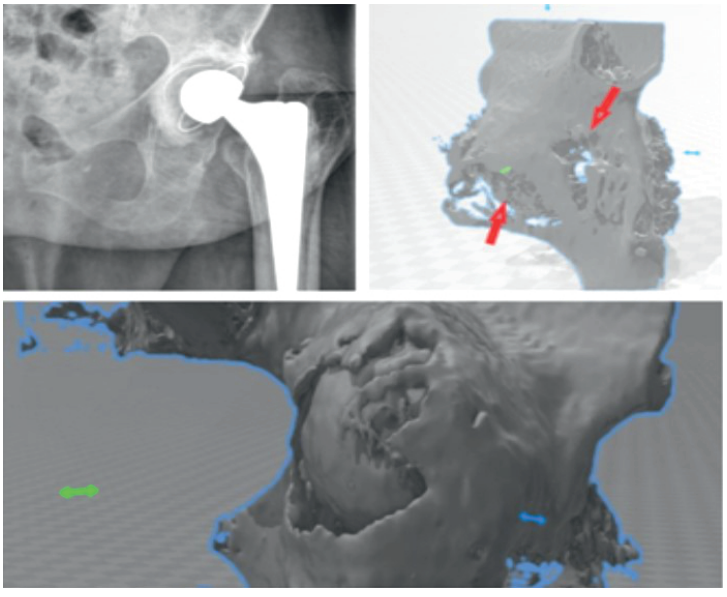


Fig. 3. Difference between X-ray and 3D estimated bone loss in the same patient and visualization of a severe central defect (IIIb)

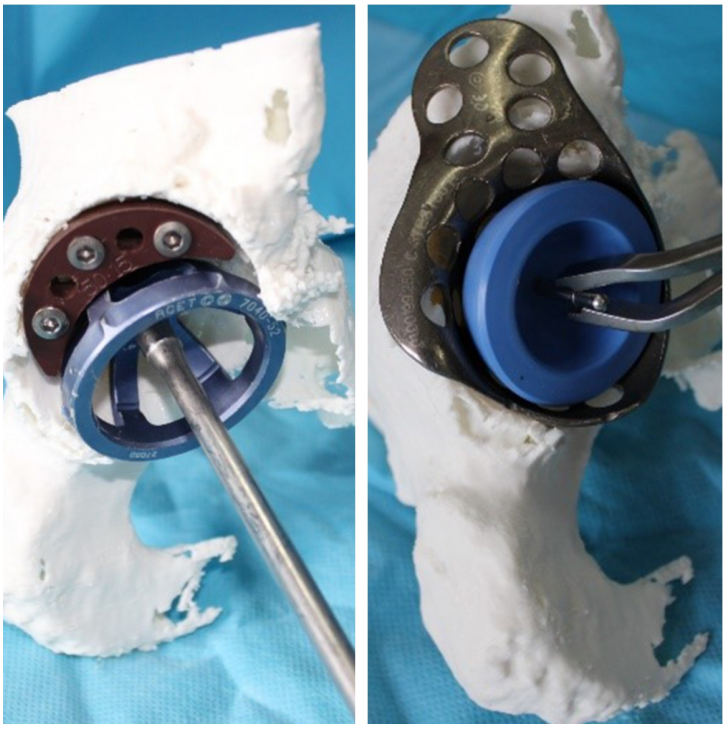


Fig. 4. Two different templates for one case including acetabulum with augmentation ant antiprotrusional cage

Fifteen cases (60%) were with exactly planned acetabular component and in ten cases (40%) planned and implanted acetabular component had difference in ± 1 size. In this series there were no cases with more than ± 1 size difference between planned and implanted acetabular components.

Biomechanical parameters were also a point of interest in this research. We measured postoperatively achieved values of centre of rotation, femoral offset and leg length discrepancy. Measurements were done on the postoperative pelvic AP X-ray. Differences between planned values of these parameters and postoperatively measured were analyzed. Centre of rotation was measured in two axes (X and Y). The average difference of the planned/postoperatively measured hip joint centre is 3.12 mm on X and 3.20 mm on Y axis. Femoral offset difference between planned and postoperatively achieved values is 5.6 mm as average. In regard to leg length discrepancy we report mean of 6.44 mm of postoperative difference of leg length. The average operative time in the series is 180.2 min.

Discussion. The use of conventional radiographies is the "gold standard" for primary hip arthroplasty, but it does not give sufficient information in cases of significant bone defects present in complex and revision arthroplasty of the hip joint. Preparation of the individual preoperative plan of patient with the use of computed tomography and 3D reconstruction in real size is a viable option in this respect. Regarding the imaging examination, the use of protocol for reduction of the artefacts provides a possibility for achievement of a model of good quality and availability of diagnostic information [19]. When the protocol is not observed, it is impossible to achieve a good anatomical model and accurate preoperative planning, respectively.

In the complex and revision surgery of the hip joint, a correct assessment of bone defects is mandatory [12, 15]. The real size of 3D models provides exceptional accuracy in this regard [14, 16, 17]. With the use of only conventional radiographies, the precise classification of the bone loss according to the generally accepted classifications is difficult [15]. At standard antero-posterior and lateral radiographies of pelvis, the absence of bone over the anterior and posterior walls cannot be determined accurately and it is almost impossible to evaluate the central defect.

The goal of preoperative planning of the reconstruction of the hip joint in cases of complex and revision arthroplasty is to achieve a stable fixation of the components in conditions of bone loss, as well as reconstruction of the biomechanics of the joint during the actual surgery [3, 7, 11]. In this regard the technique for 3D simulating and printing of anatomical models allows determination of the size of components with exceptional preciseness. Slightly under- or oversizing could be visualized by this technique. In the current report the excellent results correlate with those presented by other authors in the literature [13, 14, 16, 17].

The 3D prototypes in real size give another advantage in complex cases. The surgeon can create more than one plan for reconstruction, which is especially

beneficial in the presence of significant bone defects [12, 15]. For management of bone loss, the use of capsules of large sizes, semilunar and supporting augments, bone substitutes, and antiprotrusional cages can be taken into consideration [7, 11, 12]. In the presented cases, two main plans for reconstruction were prepared, including possible bone grafting and planning of the sizes of augments and screw fixation, which is also reported by other authors [14, 16, 17]. This helps to prepare the necessary implants for the intervention and to have plan B for possible changes in the strategy. In this way the operative time, the blood loss, and the risk of intraoperative and postoperative complications are reduced [8, 9, 14].

The method has its technical disadvantage. The materials for preparation of the models have different mechanical qualities of the native bone, which of course results beyond measure in differences in the tactile sense and ex-vivo manipulation of the model. In our series some of the simulations are reamed with the last reamer contributing to the implanted cup. Intraoperatively the last reamer is one size smaller than the acetabular cup. That could be explained by the difference between mechanical qualities of the printing material and the real bone.

Regarding the price of the technique, the preparation of the 3D printing of anatomical model requires more resources – tomographical image, specialized softwares, 3D printer, materials for manufacturing. The process demands additional time for preparation, greater radiation exposure of the patient, and well-trained workers. Nevertheless, this method is beneficial in severe cases of complex and revisional hip arthroplasty, because the possible complications would exhaust more resources for their treatment [9, 20].

The revision hip arthroplasty requires good surgical experience. Even the experienced surgeon encounters difficulties in some of the cases. Thus, the method of 3D printing gives an opportunity for training and improves the learning curve of the surgeons [17]. The orthopedic surgeon can achieve good visual and tactile sense for the concrete case which makes this method an invaluable training tool.

Conclusion. Complex and revision hip arthroplasties are a challenge for the orthopedic surgeons. The massive bone defects encountered in these cases, are difficult, both for precise diagnostics and classification, and for surgical management. Adequate preoperative preparation of the patient, correct operative approach, preoperative planning and management of resources, are of key significance for the good outcome of the operation, and for the quick and complication-free recovery.

The technique of 3D printing of an anatomical model and planning of reconstruction provides the surgeon with a visual and tactile notion of the concrete case. It allows for precise preoperative planning, including preparation of several strategies. Thus, it improves the logistics of the treatment, shortens the surgery time and the blood loss, and accelerates the recovery period with lower risk of complications. The presented method can also be used for education of inexperienced surgeons as a simulator.

The method has some disadvantages – additional costs and time, increase of radiation to the patient and need of trained personnel. Nevertheless it finds its precise application in complicated cases. The insufficient literature sources show that the presented method can be further studied and developed. The technique is described for the first time in our country and this initial experience is an important first step for a future exploration of the problem.

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