PREOPERATIVE PLANNING OF HIP ARTHROPLASTY

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Preoperative planning of hip arthroplasty provides surgeons with a unique opportunity of thorough investigation of the patient's anatomy, allows them to determine optimal implant size and position, as well as to prevent potential complication. Advances in digital technology enable expansion of opportunities of preoperative planning due to using three-dimensional modeling. The study was aimed to compare precision of the three-step preoperative planning of hip arthroplasty and the standard method. Methods: The study involved 224 patients with various forms of degenerative and dystrophic diseases of the hip joint, who were divided into the index and control groups based on the planning method. In the index group, preoperative planning of arthroplasty was conducted in three steps: assessment of bone density in the zones of fixation based on CT; virtual design involving the use of automated programs; 3D model construction based on the computer model. X-ray images and endoprosthesis templates were used in the comparison group. The results showed that there were no significant differences between planning methods in patients with osteoarthritis and avascular necrosis of the femoral head ($p > 0.05$), in contrast to the group with traumatic hip joint pathology showing significant differences ($p_c = 0.002$). Conclusions: the three-step algorithm for preoperative planning of hip arthroplasty showed higher efficacy in patients with various nosological forms of degenerative and dystrophic diseases of the hip joint compared to the standard method.

Keywords: hip replacement, arthroplasty, preoperative planning, volumetric modeling, 3D printing

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Compliance with ethical standards: the study was approved by the Ethics Committee of the Bashkir State Medical University (protocol № 11 dated 15 November 2023)

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ПРЕДОПЕРАЦИОННОЕ ПЛАНИРОВАНИЕ АРТРОПЛАСТИКИ ТАЗОБЕДРЕННОГО СУСТАВА

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Предоперационное планирование артропластики ТБС предоставляет хирургам уникальную возможность тщательного изучения анатомии пациента, позволяет определить оптимальный размер, позиционирование импланта, а также предупредить потенциальные осложнения. Развитие цифровых технологий позволяет повысить возможности предоперационного планирования за счет использования трехмерного моделирования. Цель: провести сравнение точности трехэтапного предоперационного планирования артропластики ТБС по сравнению со стандартным методом. В исследование было включено 224 пациента с различными формами дегенеративно-дистрофических заболеваний ТБС, которые были разделены на основную и контрольную группу в зависимости от метода планирования. В группе исследования предоперационное планирование артропластики проводилось в три этапа: оценка плотности костной ткани в области опорных зон на основании КТ-томографии; виртуальное проектирование с использованием автоматизированных программ; изготовление 3D-модели на основе компьютерного моделирования. В группе сравнения использовали рентгенограммы и шаблоны эндопротеза. Результаты показали, что статистически значимой разницы между методами планирования не было у пациентов, страдающих остеоартрозом и аваскулярным некрозом головки бедра ($p > 0{,}05$), в отличие от группы с посттравматической патологией ТБС, у которой отмечалась статистически значимая разница ($p_к = 0{,}002$). Выводы: алгоритм трехэтапной методики предоперационного планирования артропластики ТБС показал более высокую эффективность для пациентов с различной нозологической формой дегенеративно-дистрофических заболеваний ТБС по сравнению со стандартным методом.

Ключевые слова: эндопротезирование тазобедренного сустава, артропластика, предоперационное планирование, объемное моделирование, 3D-печать

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In recent decades, the share of high-tech medical care in traumatology and orthopedics dramatically increased, including endoprosthetic replacement of major joints in the lower limbs: hip and/or knee joint [1]. Total hip replacement (THR) is a standard surgical procedure used for treatment of severe disorders [2]. The main purpose of hip replacement is pain relief and functional lower limb restoration allowing the patient to return to active role and improve his/her quality of life. When performing total hip replacement (THR), the endoprosthesis acetabular component and stem should have appropriate component size and position, which is essential for achieving good functional outcome and longevity of the prosthesis. However, incorrect positioning or sizing of the endoprosthesis components increases the risk of intraoperative and postoperative complications, such as limb lengthening or shortening, intraoperative fractures, aseptic loosening, dislocation of the endoprosthesis head, etc. [3]. All these contribute to postoperative pain in the operated joint, instability and premature failure of the endoprosthesis components, thereby bringing dissatisfaction to the patient and reducing his/her quality of life [4]. Joint replacement of any type requires preoperative planning and intraoperative control. Preoperative planning is of utmost importance for optimization of the THR outcome. It helps the surgeon to visualize the final implant position after thorough assessment of clinical and radiography data [5]. In case of primary arthroplasty, preoperative planning can be performed using standard x-ray images, 2D templates or appropriate software. When performing primary arthroplasty in patients having a history of injury, osteotomy, surgical procedures, preoperative planning is hampered by non-compliance with the radioanatomical criteria.

Superimposition of the endoprosthesis templates onto the standard x-ray image of the hip joint for accurate sizing and positioning of the acetabular and femoral endoprosthesis components represents a conventional method of preoperative planning of THR.

Three-dimensional planning makes it possible to more clearly define the patient's unique anatomical features and reference points and ensures optimal visualization for preoperative implant sizing. The 3D planning methods allow one to more accurately determine the size of the endoprosthesis acetabular component and stem (96–100%) compared to 2D templates (16–43%). The results confirm superiority of 3D methods over 2D templates in terms of implant sizing accuracy. The computed tomography data used in 3D planning represent an appealing alternative to navigation for restoration of the limb length and axis [6–9].

The lack of unified approaches to planning of surgical treatment prevents achieving identical treatment outcomes in similar clinical situations. It is necessary to create certain preoperative planning algorithm for selection of treatment tactics in patients with various joint disorders.

The study was aimed to compare the effectiveness of the three-step preoperative planning of hip arthroplasty based on the nosological form of degenerative and dystrophic disease of the hip joint and that of the standard method.

METHODS

Comparative analysis of outcome estimates for various methods of preoperative planning of THR was conducted. A total of 224 patients were enrolled. Inclusion criteria: grade III–IV (Kellgren & Lawrence classification) primary (idiopathic) osteoarthritis of the hip associated with grade III or more joint function impairment; grade II–III aseptic necrosis of the femoral head with severe pain; post-traumatic condition (condition after osteosynthesis for proximal femur or acetabulum fractures) with complications in the form of post-traumatic ostheoarthrosis or nonunion, and individuals in need of hip arthroplasty. The diagnosis was established based on the clinical and anamnestic data, as well as using instrumental assessment methods (radiography, computed tomography and magnetic resonance imaging). Exclusion criteria: infectious inflammatory disease of the

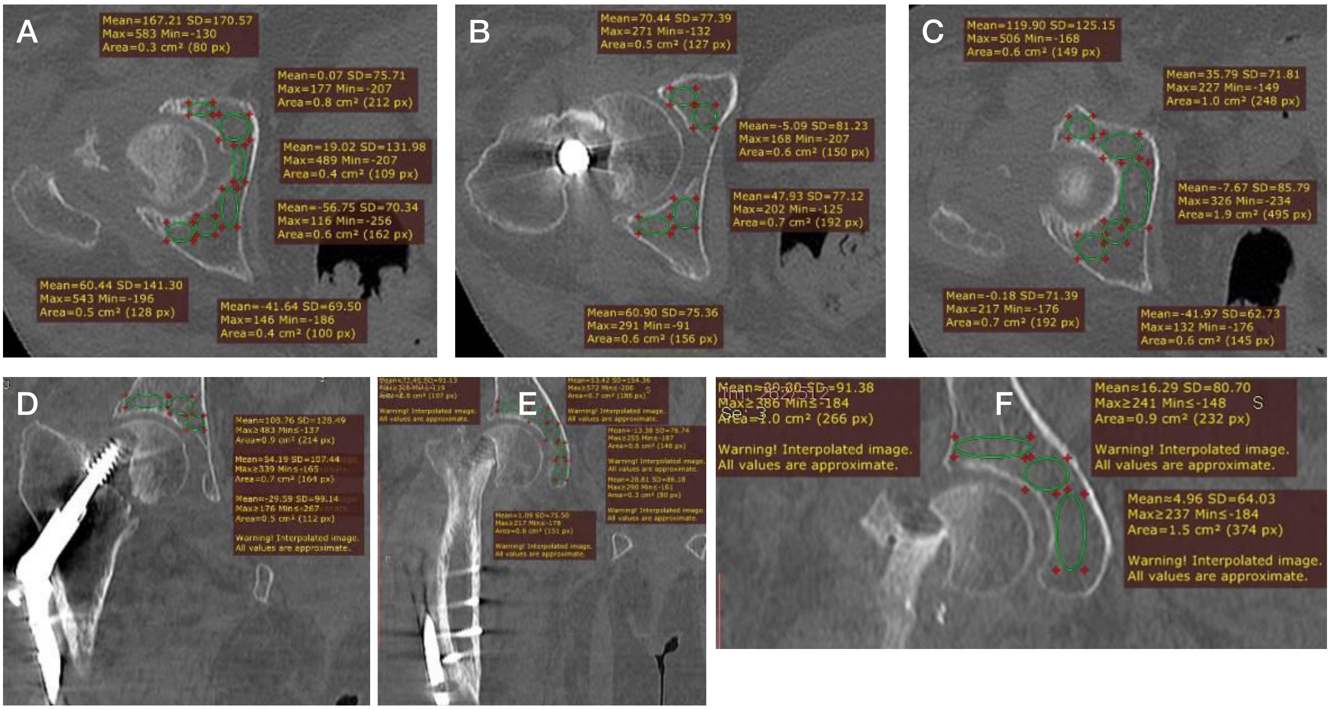

Fig. 1. Determination of bone density in the zones of fixation located in the acetabular area based on the horizontal **(A**, **B**, **C)** and frontal **(D**, **E**, **F)** CT scans of the 73-year-old patient: at the level of inferior acetabulum **(A)**; at the level of the acetabulum middle part **(B)**; at the level of superior acetabulum (**C**) (Average total bone density according to the Hounsfield scale — 30.65 HU.); at the level of posterior acetabulum **(D)**; at the level of the acetabulum middle part **(E)**; at the level of anterior acetabulum **(F)**. (Average total bone density according to the Hounsfield scale — 30.09 HU.)

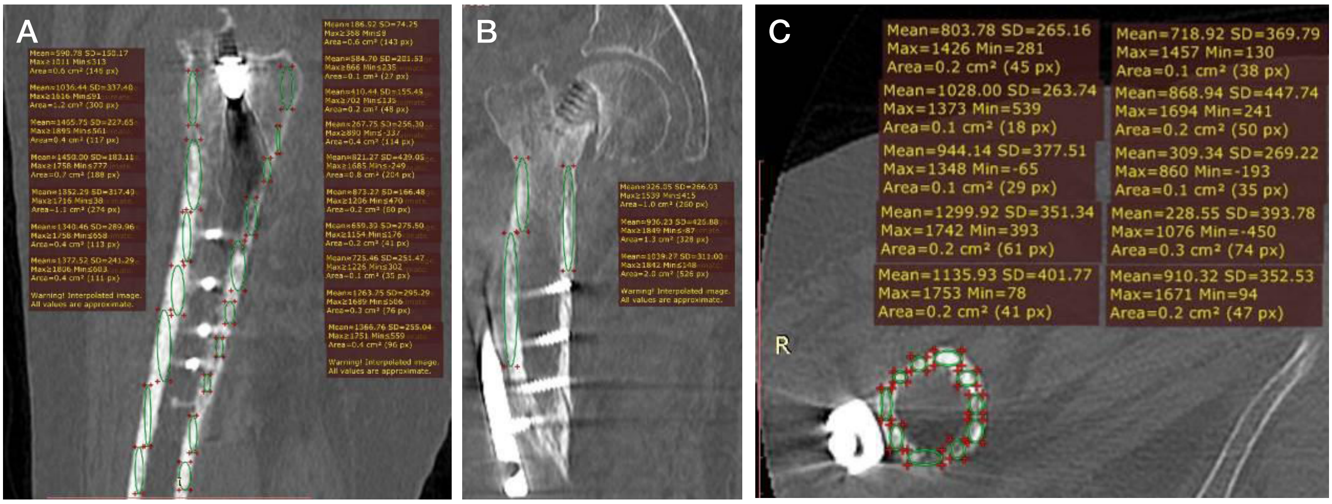

Fig. 2. Determination of bone density in the zones of fixation located in the acetabular area based on the sagittal, horizontal and frontal CT scans of the 73-year-old patient. **A**. Bone density estimation based on the sagittal scan. **B**. Bone density estimation based on the frontal scan. **C**. Bone density estimation based on the horizontal scan. (Average total bone density according to the Hounsfield scale — 869.13 HU.)

affected segment; concomitant somatic disorders representing absolute contraindications to surgery; no informed consent submitted by the patient, age under 18 years. All patients were divided into two groups: index group (116 people) and comparison group (108 people). The index group was divided into three subgroups: 34 patients with ostheoarthrosis (average age 60.8 ± 7.2 years), 30 patients with avascular necrosis of the femoral head (average age 43.9 ± 7.9 years), 52 patients with post-traumatic hip joint disorders (patients of this group underwent osteosynthesis for fractures of the femoral neck, trochanter region of the femur, acetabulum of the pelvis, etc.) (60.2 ± 11.1 years). The comparison group was also divided into three subgroups: 33 patients with ostheoarthrosis (average age 61.3 ± 6.8 years), 29 patients with avascular necrosis of the femoral head (42.6 ± 8.4 years), 46 patients with post-traumatic hip joint disorders (59.3 ± 12.7 years). The average age of all surveyed patients was 57 ± 6.2 years, 119 people (53.12%) were females, 105 people (46.87%) were males.

In the index group (n = 116), preoperative planning of hip arthroplasty was performed in three phases.

In the first phase, bone density in the acetabular and femoral areas was determined in three planes based of the hip joint computed tomography (CT) data using the Hounsfield scale. Bone density was assessed around the perimeter of the zones of fixation considering the planned implant location and installation site. Determination of the zone with optimal bone density and the regions with reduced bone density, osteosclerosis, cysts and various defects was an important criterion of the endoprosthesis installation and positioning. When performing preoperative planning in patients having a history of osteosynthesis, it was difficult to determine bone density in the zones of fixation due to the presence of "metal artifacts" (Fig. 1 and 2).

In the second phase, the TraumaCad v. 2.4 software (Brainlab; USA) was used to determine the optimal size and position of the endoprosthesis components. For that x-ray image of the pelvis with the hip joint was uploaded to the program, over which the digital template of the endoprosthesis femoral and acetabular components was superimposed. However, when performing preoperative planning of endoprosthetic replacement using software, complete proximal femur visualization was hampered by the presence of surgical hardware (Fig. 3).

In the third phase, the Geomagic Studioc (Raindrop Geomagio Inc.; USA) and 3D Slicer (Copyright 2023, Slicer Community; USA) software was used for virtual installation of the endoprosthesis components following construction of a volumetric model of the baseline condition (Fig. 4). This phase enabled estimation of the segment anatomy distortion, more accurate adjustment of the endoprosthesis positioning, provision of starting biomechanics, and determination of the hip arthroplasty tactics. In cases of severe hip joint deformities,

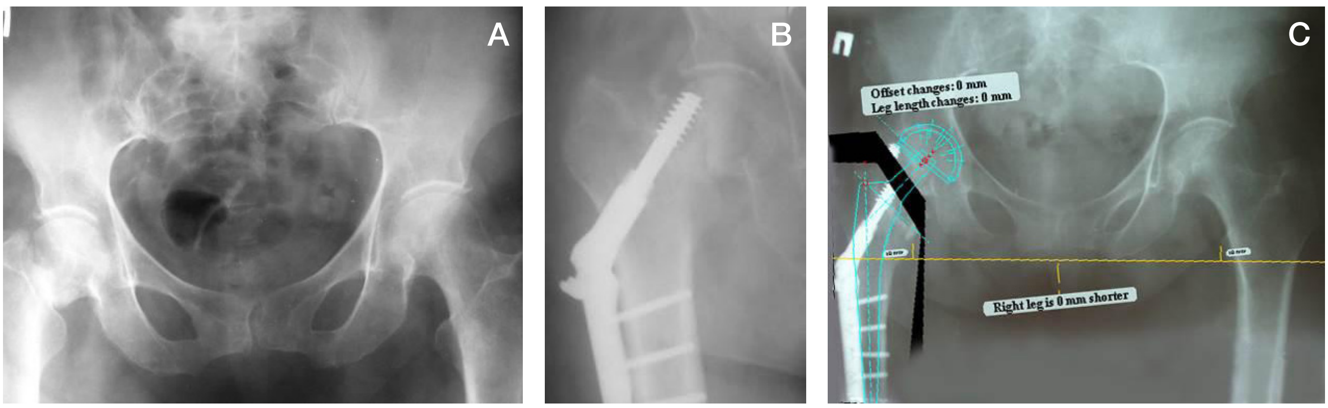

Fig. 3. Survey frontal x-ray image of the pelvis and the right hip joint of the 73-year-old patient. Diagnosis: condition after osteosynthesis involving the use of the DHS system. False joint of the right femoral neck. **A**. X-ray image acquired at admission to surgery — osteosynthesis of the right femur involving the use of the DHS system. **B**. X-ray image acquired after osteosynthesis involving the use of the DHS system. **C**. Sizing and positioning of the endoprosthesis components using the TraumaCad v. 2.4 software. (Planned size of the acetabular component — 50, femoral component — 4)

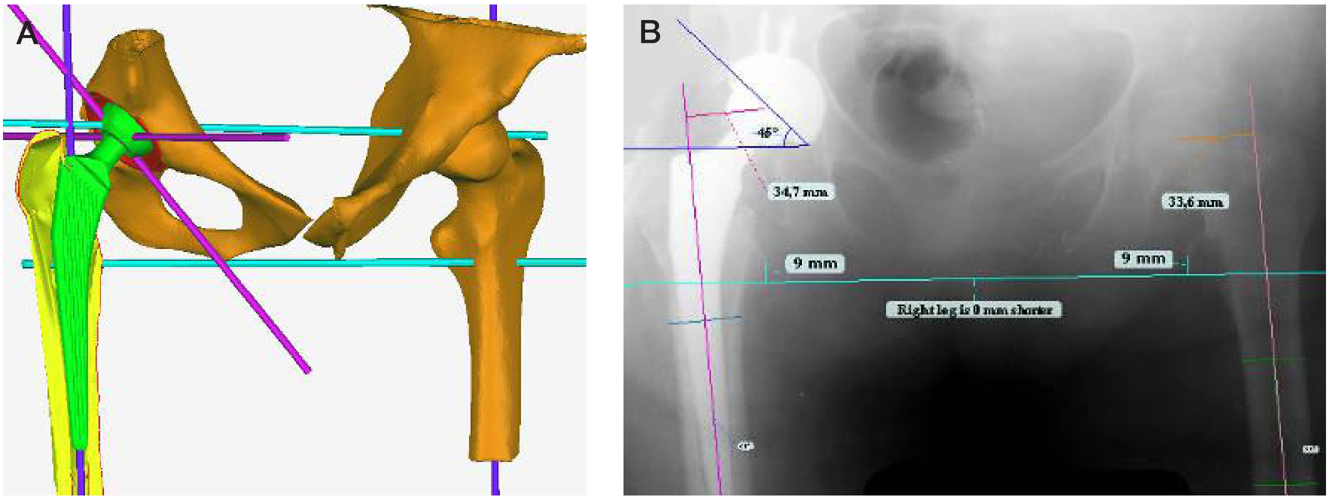

Fig. 4. Female patient, 73 years. Comparison of the endoprosthesis component dimensions during preoperative planning based on volumetric modeling performed before and after hip arthroplasty. **A**. Volumetric model of the right hip joint with virtual installation of the endoprosthesis components (planned size of the acetabular component — 52, femoral component — 6). **B**. Survey x-ray image of the pelvis and right hip joint after installation of endoprosthesis, the dimensions of acetabular and femoral components corresponded to the planned dimensions

computer modeling was combined with 3D printing of the affected segment before and after hip arthroplasty (Fig. 5).

In the control group (n = 108), preoperative planning was performed by standard methods: posterioanterior x-ray images of the pelvis with the hip joint were used, over which the templates of the endoprosthesis components (draft) were superimposed to determine the implant size.

Preoperative planning was followed by surgical treatment, THR, in both studied groups.

RESULTS

The results were assessed based on the match of the endoprosthesis component dimensions determined before and during surgery (intraoperatively). The index group patients with osteoarthritis and avascular necrosis of the femoral head showed higher implant sizing accuracy, however, it was comparable with that of the control group ($p > 0.05$). The subgroup with post-traumatic disorders showed significant differences in the accuracy of the intended endoprosthesis component size determination between the index and the control groups ($p_c = 0.002$). The main results and the implant sizing accuracy depending on the disease entity and the preoperative planning method are provided in Table 1 and Fig. 6.

DISCUSSION

Comparability of the results of the index and control group patients with osteoarthritis and aseptic necrosis could result from minor anatomy distortion in the segment of the pelvis and the lower limb, while in patients with post-traumatic disorders the planned endoprosthesis component dimensions in controls did not match actual size in more than a half of cases, which suggested low effectiveness of standard planning method

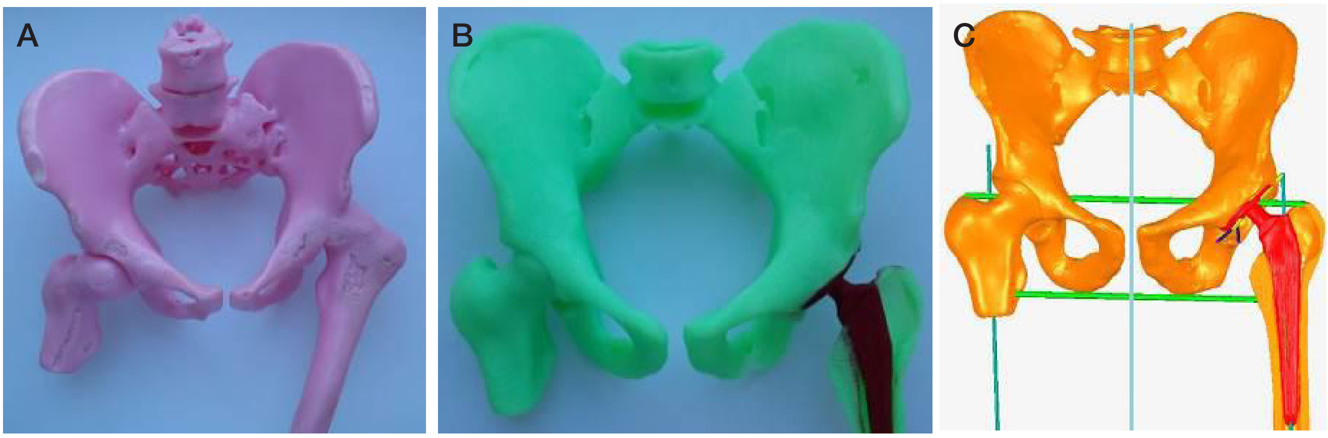

Fig. 5. Patient, 45 years. Preoperative planning based on volumetric prototyping. **A**. Printed 3D model of the hip joint before arthroplasty. **B**. Printed 3D model of the hip joint after arthroplasty. **C**. Preoperative planning of the right hip arthroplasty based on volumetric modeling

Table 1. Endoprosthesis component sizing accuracy depending on the nosological form of degenerative and dystrophic disease of the hip joint (%)

	Osteoarthritis (subgroup I)		Avascular necrosis of the femoral head (subgroup II)		Post-traumatic disorder (subgroup III)	
	Control group	Index group	Control group	Index group	Control group	Index group
Number of people	n = 33	n = 34	n = 29	n = 30	n = 46	n = 52
Endoprosthesis component sizing accuracy (%)	81.82	85.29 (p_c = 0.7)	82.76	86.67 (p_c = 0.68)	47.83	78.85 ($p_{к}$ = 0.002)

Note: p_c — significance of differences from controls.

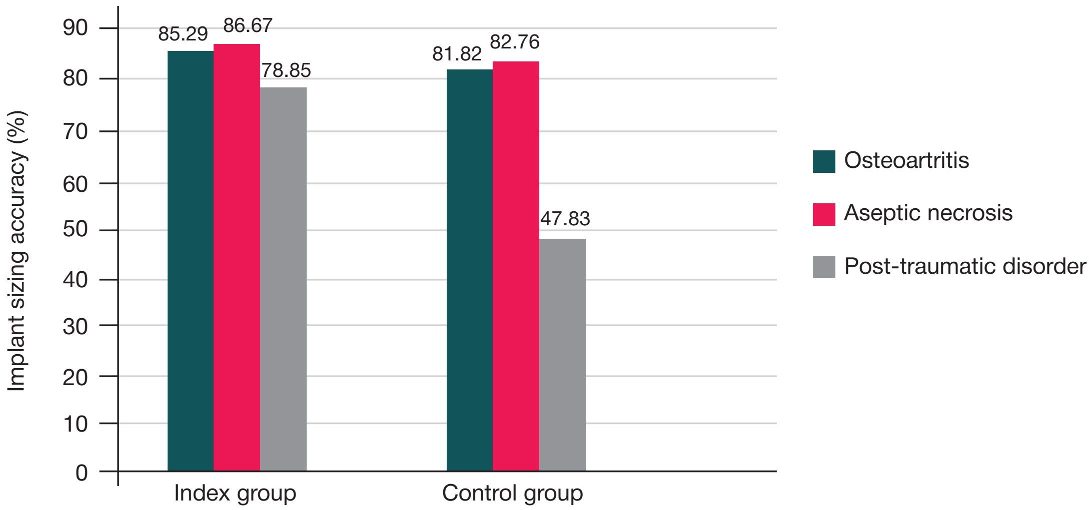

Fig. 6. Implant sizing accuracy when using different preoperative planning methods

in this group of patients due to more prominent segment anatomy distortion resulting from fractures, osteosynthesis or reconstructive surgery, as well as to the hip joint anatomy distortion, impaired joint congruence, secondary pelvic and spinal deformities, lower limb shortening by more than 3 cm [10–12].

The analysis resulted in creation of the algorithm for selection of preoperative planning method based on the forms of degenerative and dystrophic diseases of the hip joint and severity of the hip joint anatomy distortion (Table 2).

CONCLUSIONS

The proposed approach to selection of preoperative planning technique makes it possible to accurately determine the endoprosthesis component dimensions and contributes to correct orientation and positioning of the endoprosthesis components during hip arthroplasty. The proposed algorithm of the three-step method showed higher effectiveness of preoperative planning and personalized design for patients with various nosological forms of degenerative and dystrophic diseases of the hip joint compared to the standard method, it also enabled accurate endoprosthesis component sizing. Preoperative planning of hip arthroplasty by the proposed method allows one to assess the disease characteristics at the local and systemic levels. The most challenging situations are observed in patients with post-traumatic disorders of the hip joint. This is due to the fact that patients of this group usually show severe bone disruption in the femoral and acetabular zones of fixation.

Table 2. Selection of preoperative planning technique based on the form of degenerative and dystrophic disease of the hip joint

Groups of patients	Preoperative planning phases
Patients with avascular necrosis of the femoral head, primary osteoarthritis and no prominent anatomy distortion	Determination of bone density in the acetabulum and zones of fixation based on CT in accordance with the Hounsfield scale Using the automated software to determine the endoprosthesis component dimensions based on 2D design
Patients with avascular necrosis of the femoral head, primary osteoarthritis and prominent anatomy distortion (secondary deformities of the spine and pelvis, rigidity, lower limb shortening by more than 3 cm) Patients with post-traumatic disorders of the hip joint having a history of various types of proximal femur surgery (osteosynthesis) or acetabular fractures	Determination of bone density in the acetabulum and zones of fixation based on CT in accordance with the Hounsfield scale Using the automated software to determine the endoprosthesis component dimensions based on 2D design Preoperative planning involving construction of volumetric 3D models

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