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Compensation of acetabular defects in hip arthroplasty

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Abstract

Acetabular reconstruction is a necessary condition for improving the survival rate and proper functioning of the implant. The issue of compensation for bone loss remains one of the most difficult and controversial in orthopaedics. The article aimed to analyze approaches to the problem of management of acetabular defects in hip replacement. The paper presents the key features of the anatomy and radiological anatomy of the acetabulum. Modern modifications of acetabular components of an endoprosthesis, their advantages and disadvantages, as well as ways to compensate for acetabular bone loss with bone substitute materials are considered. The review highlights the use of 3D printing technologies, the interaction between physicians and other experts in this field. Currently, an active search for materials, alternatives to autogenous bone, as well as ways to facilitate the design and reduce the negative impact of the implant on the patient's bone tissue continues. The use of additive technologies seems to be the most promising direction that allows applying an individual approach to each clinical case, but it is available only in specialized centres and is associated with significant material, technical and legal difficulties. Stable fixation of the acetabular component, according to the literature, is achieved under the condition of restoration of hip rotation centre in the native acetabulum area, restoration of normal anatomical relations in the hip joint and adequate replacement of bone loss.
Keywords: acetabulum, arthroplasty, bone defect, review.

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In complex cases, revision arthroplasty of the acetabular component remains a debatable aspect of modern traumatology. Compensation for bone density in the acetabular region enables achieving endoprosthesis cup stability, anatomically correct relationship of components, and joint rotation center restoration, which reduces the risk of repeated revisions [1, 2].

A wide range of materials and techniques for restoring bone density in the acetabular region has been developed. Autoplasty and allografts remain relevant. Hemispherical cups with a porous osseointegrative surface, also fixed to the bone with screws, are widespread. Specialized devices are gradually being introduced into practice, namely large-diameter hemispherical cups (jumbo cup), oval-shaped acetabular components (oblong/bilobed cup), trabecular metal products, cages (special inserts between the receptive bone bed and the acetabular component of the prosthesis), which protect against protrusion, and three-flange acetabular components manufactured using additive technologies [3, 4]. The doctor chooses, depending on the clinical situation, since all the methods presented have advantages and disadvantages.

Autologous bone and allografts can quickly undergo resorption, causing instability of the components [5, 6]. Nonreworkable materials in the case of extensive defects, such as IIIA and IIIB, according to Paprosky, are preferable since they provide stable fixation. As a rule, the disadvantage of this category is a high modulus of elasticity, which can lead to tissue lysis of the receptive bone bed [7].

Additive technologies enable the creation of individual ceramic constructions for filling bone defects, including those in the supraacetabular region. Using such technologies will simplify surgery, as it will enable using a standard pelvic component without massive supporting structures (Burch-Schneider ring, Muller ring), facilitate construction, reduce the number of metal elements in the body, prevent potential reactions to metal, and create optimal conditions for osseointegration because of the formed microstructure of the implant [8].

This work analyzes approaches to solving the problem of replacing acetabular defects in hip arthroplasty.

This paper analyzes literature sources over the past 10 years for the keywords "acetabular revision" and "acetabular defect." The search

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was performed using the PubMed database and eLIBRARY. Only full-text articles were analyzed. For the queries "acetabular defect" and "acetabular revision," 954 publications containing information on defects in revision arthroplasty were found during the specified period. Also, 348 publications provided data on options for filling acetabular defects. Fifty-eight sources were selected out of the publications found, containing the most complete, relevant, and credible information in the opinion of the team of authors.

It is necessary to assess the type and severity of the acetabular defect, according to various classifications to make a clinical decision regarding the choice of the acetabular component of the endoprosthesis and osteoreplacement material. This requires knowledge of anatomy and radiological anatomy of the acetabulum [9].

Characteristic of the acetabular region anatomy. Several authors distinguish four columns of stability of the acetabulum. Namely, the external one is the acetabular roof; the internal one constituting the bottom of the acetabulum; the anterior aspect, formed by the pubic bone; and the posterior, formed by the ischial bone [10].

The thickness of the acetabulum bottom averages 3.6 ± 0.4 mm. The front wall has a thickness of 7.6 ± 0.3 mm and varies from 4.0 to 15.0 mm. The thickness of the posterior and lower walls of the cavity is from 4.0 to 21.0 mm [2].

The acetabular roof and the acetabular fossa differ significantly in the thickness of the cortical layer. In the area of the fossa, it is only 1 mm, while in the roof area, its thickness is up to several millimeters [11]. The greatest thickness of the compact substance is in the lunate surface region since this is the most loaded part of the cavity. The anterior edge of the acetabulum is a continuation of the lower edge of the superior branch of the pubic bone and is traced toward the acetabular upper edge.

X-ray anatomical criteria of the acetabular region. It is necessary to lower the perpendicular from the acetabular edge to determine the normal position of the femoral head. The normal position of the head is inward from the perpendicular. The acetabular roof usually is oriented horizontally. The projections of the anterior and posterior edges of the cavity do not normally overlap. The acetabulum bottom represents a semicircle and consists of a fossa and a roof. The "tear figure" defines the anterior part of the ischial bone body and the acetabular bottom. The lateral contour of the "tear figure" is also the acetabular bottom in its fossa region. It passes into the acetabular roof, which corresponds to the articular surface [12].

Four different sectors were determined to conduct a detailed analysis of defects, namely, the cavity roof, the anterior column, the posterior column, and the medial wall., Bone tissue loss in the ilium, pubis, and ischium is also considered, where applicable, to account for defects extending beyond specific sectors around the acetabulum [13]. Threshold values of 15% and 25% were used to define clinically significant mass from non-critical bone loss or bone loss caused by measurement inaccuracies. Combined with the assumption that the posterior column is critical to implant stability, a threshold greater than 15% in the posterior region and one greater than 25% in the cranial, anterior, and medial regions were determined to detect clinically significant bone loss [14].

Morphological studies. Koob et al. analyzed bone loss in various parts of the acetabulum in patients undergoing repeated hip arthroplasty. The greatest relative loss of bone volume was detected in the medial wall with median and percentile values of 72.8% (50.6%; 95.0%). The ovality was 1.3 (1.1; 1.4), the lateral angle between the center and the margin was 30.4° (21.5°; 40.4°), and the total implant migration was 25.3 (14.8; 32.7) mm [15].

In addition, a correlation was revealed between implant migration in the cranial direction and the relative bone volume loss in the cavity roof ($R = 0.74$), and ovality ($R = 0.67$). The authors of the study investigated the relationship between impaired medial acetabular wall and acetabular complications after total hip replacement in a cohort of patients who were allowed to load the joint immediately fully. The medial defect was considered as an acetabular protrusion beyond the Kohler line. In this cohort, a quarter of patients had radiological signs of damage to the medial acetabular wall. However, the medial wall injury determined radiographically did not correlate with an increased risk of secondary migration, dislocation, fracture, or pain. None of the revision surgeries were performed in the study group, and all were limited to the femoral component [16].

These results are consistent with those of biomechanical studies [17] that showed the instability of acetabular components implanted in cadavers with a medial defect only under loads exceeding physiological thresholds. It is known that the contact forces of the hip joint in the acetabulum of a 75–kilogram person range from 1543 to 2116 N during routine activities. A biomechanical cadaveric study reported acetabular fractures after total arthroplasty with an average load of 4221 N in the group with a 2 cm medial wall defect. Therefore, a large margin of safety exists between routine *in vivo* loading and the fracture point.

It has also been revealed that peak contact forces can increase up to 3600 N in patients with impaired gait patterns and 5300–6400 N when stumbling. These values can compromise the acetabular wall and lead to a fracture. Walking with crutches can significantly reduce the incidence of stumbling in these patients, thereby limiting the risk of peak forces acting on the acetabular component, whether the patient is allowed to put weight fully on the operated limb or not.

Complex primary and revision hip surgeries reveal that intentional disruption of the medial wall by the "medial protrusion technique" does not correlate with complications associated with the acetabular component. An interesting study was conducted [18], where three-dimensional models helped plan a complex intervention. With 3D models, the researchers checked and classified acetabular defects and planned the reconstruction method for the acetabulum and stable fixation of the components during the revision.

Systematization of acetabular defects: The classification of acetabular defects has been developed for adequate preoperative planning and surgical approach determination. Classifications also enable comparing the results of different techniques for the same type of defect.

The classifications are based on various principles. Nowadays, the Paprosky classification is the most commonly used [19]. This classification is based on four basic radiological signs, each reflecting the lesion severity of one of the cavity departments. Visualization of the Kohler line indicates the state of the medial wall and anterior column of acetabular stability. The "tear figure," in addition to the state of the medial wall, reflects the state of the posterior and lower parts of the anterior column. Lysis of the ischium indicates damage to the posterior wall and posterior column. When the cavity dome is damaged, vertical migration of the endoprosthesis cup occurs [20, 21].

This classification needs to be supplemented with current data from computed tomography (CT) studies, enabling improved visualization accuracy for preparing personalized implants using 3D defect modeling technologies. Additional information is also required on the limited or unlimited nature of the defect and pelvic ring stability [22, 23].

Classifications of the American Academy of Orthopedic Surgeons (AAOS, 2017) [20] and Gross (1993) modified by Saleh (2001) [13] are also based on anatomical landmarks. They enable the location and nature of the defect to be characterized more accurately than the classification of Paprosky (1994) [19, 24], but do not reflect its severity. The classifications of Gross (1993) [14] and Parry (2010) [22] are based on the amount of bone loss. Gross classification (1993) can only be applied directly during surgery was developed to justify the use of various allografts.

Hip arthroplasty in trauma of the acetabulum. Trauma is one of the most common causes of defects in the acetabular bone tissue. According to various sources, the incidence of acetabular fractures ranges from 2% to 24% of all pelvic fractures. In 60%–80% of cases, a fracture occurs due to traffic accidents, and in 20%–40% of cases, it is caused by a catatrauma [25, 26]. Acetabular fractures result from high-energy trauma in young patients and low-energy impact in older patients. Indications for surgical treatment are acetabular fractures with displacement of fragments and multiplanar fractures affecting the loaded part of the acetabulum, posterior wall fractures, intraarticular fragments, incongruence in the joint, and depression of the articular surface [27, 28].

There are several approaches to the surgical treatment of acetabular fractures. There are no consensus or clear indications for one approach or another. The age of the patient, the presence of concomitant pathology that affects the rate of bone regeneration, the nature of the fracture, and the quality of bone tissue are the most significant. The prognosis is determined based on these factors and preference is given to one or another method. The choice remains between open reduction with internal fixation, early primary hip arthroplasty, or a combination of these methods [27, 29].

Exclusively open reduction and internal fixation are preferred in younger patients, and total arthroplasty is the treatment of choice in older patients. At the same time, in most cases, cement augments, support rings, or cages are required to compensate for bone density and achieve acetabular component stability. Many authors believe that open repositioning and internal fixation with plates or screws with hip arthroplasty should be the best option. This can significantly reduce the risk of complications and the number of repeated surgeries, especially in older patients [26–30].

In revision prosthetics of the acetabular component, cemented and cementless cups and anti-protrusion rings are used. Cups with press-fit fixation and additional fixation with screws are preferred, as they demonstrate good survival at medium- and long-term follow-up. Successful osseointegration of the acetabular component is feasible when the contact area between the implant and living bone is at least 50%. Successful osseointegration is also facilitated by roughening the surface of the cup in contact with the bone bed (using titanium plasma spraying or applying calcium phosphate coatings) or high porosity with small pore size. Highly porous metal coatings have appeared under various trade names, such as Regenerex (Biomet), Tritanium (Stryker), Gription (DePuy), Stiktite (Smith and Nephew), and trabecular metal (Zimmer) [31].

In cases of moderate bone density, a large-diameter pelvic component (jumbo cup) can be used. The method is technically straightforward, while lateralization and a slight downward displacement of the rotational center of the hip joint occur, which brings the biomechanics closer to normal in cases there were initial protrusion and cranialization of the cup. The contact area of the cup with the bone bed is large enough for successful osseointegration. This method is inapplicable in cases of large defects, and oval-shaped defects, since with this shape, the defect cannot be filled by the cup itself, and excessive processing of the anterior or posterior column or a very high cup position is required. The component stability was maintained in 80%–85% of cases during a 10-year follow-up period [31].

In cases of an extensive defect in the acetabular roof, oblong-cup acetabular components are used. They are elongated cups consisting of two halves. At follow-up periods of more than five years, the survival rate reaches 80%, while with longer follow-up periods, the indicators decrease [32].

When the defect is localized in the acetabular roof, an alternative may be to place the cup above the true center of the joint rotation. The advantage of this method is its technical simplicity; however, there are several disadvantages due to which it is used extremely rarely. First, due to the anatomical narrowing of the ilium above the cavity, it is necessary to install a cup of a smaller diameter, which contributes to dislocation. The joint biomechanics is impaired, which can cause lameness and re-development of the component instability [33, 34].

Anti-protrusion structures have become widespread. Their advantage is that they evenly distribute the load on the ilium and ischium and are easily combined with additional methods, such as bone grafting with various materials and osteosynthesis of the posterior acetabular column, thereby increasing the chances of a high survival of the component [35, 36].

In cases of pelvic ring integrity impairment, the bone walls at the rupture site are wedged. This is the so-called distraction method to achieve stability of the acetabular component. In this case, most often, an elliptical-shaped cementless cup is installed, if necessary, supplemented with bone grafting [37, 38].

The choice of the optimal osteoreplacement material is difficult. The key factor is the defect size. With small defects of degrees I and II, according to Paprosky, the use of autografts or allografts, and their combinations, is acceptable. For defects of degree III and higher, according to Paprosky, it would be preferable to use a non-resorbable material or a combination of non-resorbable and resorbable materials, where each of the grafting components will solve a specific problem. Achieving implant stability is inextricably associated with osseointegration success. For this reason, preference is given to cementless structures when the bone and implant become a single system [39, 40].

Particular attention is paid to developing strong, highly porous surfaces with a low modulus of elasticity and developed architectonics, creating the best conditions for osteogenesis [26, 41].

Successful osseointegration and the achievement of stable fixation depend on many factors. The most important are the bone tissue viability of the receiving bed, adequate blood supply to the bone, and its mechanical characteristics. These factors depend directly on the age and comorbidities in the patient. The mechanical compatibility of the material and bone tissue, and the chemical and biological characteristics of the implant, its surface properties, and the contact area with the bone bed, are also extremely important [42, 43].

Allografting remains the most common option for bone grafting. The use of crushed allograft for small defects has proven to be a reliable and effective method [44–46]. An extensive defect of types IIB, IIIA, IIIB causes technical difficulties for the application of this method and is associated with many complications, according to Paprosky (1994). The surgery's success largely depends on the rate of subsequent graft vascularization. With its rapid course, the allobone is completely replaced by the patient's bone tissue, creating a strong support for the pelvic component. A massive allograft, due to its delayed revascularization, can be resorbed rapidly, resulting in instability. The level of complications when using alloplasty for defects of types IIIAa and IIIB, according to Paprosky, ranges from 22% to 45%. The combination of anti-protrusion cages and alloplasty for such defects enables achieving primary stability. However, with long-term follow-up, the complication rate ranges from 10% to 65% [47, 48].

Trabecular metal has proven itself well as a material for augmenting and manufacturing acetabular endoprosthetic components. The combination of high porosity and low modulus of elasticity, close to the bone tissue characteristics, creates optimal conditions for osseointegration. In this case, 50% of the direct contact area of the trabecular metal with the bone is sufficient. This is convenient when performing complex revisions, accompanied by a pelvic ring rupture or extensive bone defects. If additional fixation is required in such material, holes for screws can be formed directly during surgery using a high-speed drill. The survival rate of such augments is over 90% in the early stages and over 80% in medium- and long-term follow-up [49, 50].

To date, ceramics based on zirconium compounds are successfully used in surgical traumatology and orthopedics for the manufacture of components for friction pairs. It demonstrates better wear resistance than other materials. Zirconium ceramics are characterized by good mechanical characteristics, low corrosion potential [51], lack of cytotoxicity, and minimal affinity for bacterial adhesion, which determines the possibility of studying it as an osteoreplacement material [52, 53].

Additive 3D modeling technologies are gradually gaining greater significance and distribution in complex acetabular component revisions [2, 54]. It is advisable to use individual hardware in isolation or combination with other osteoreplacement materials for defects of types IIB, IIIA, and IIIB, according to Paprosky. This is facilitated by developing CT and software that enables accurate quantification of the bone loss amount in different acetabular sectors and model creation with specified characteristics based on the images obtained. Custom triflange acetabular components from various materials are manufactured by 3D printing, according to the individual patient characteristics, which provide a good functional result [55, 56].

The creation of three-dimensional pelvis models with an acetabular defect for preoperative planning consists of several stages:

– selection of CT data;

– masking of the pathological zone and the use of a statistical shape model for the reconstruction of the native pelvis;

– transformation of the CT data set into a solid model of the pelvis, including the defect;

– transformation of the reconstruction based on the SSM mode into a solid model of the native pelvis [2].

Individual components ensure maximum contact of the hardware with the ilium, ischium, and pubis. The cup is oriented at the required angles (anteversion 15°, abduction 45°). The cup diameter is selected individually with the possibility of using heads of large diameter or dual mobility. The complex shape of bone defects is always considered, a porous surface is created to improve osseointegrative properties, and individual orientation of screw holes is also possible.

Several problems are associated with additive technologies, which are widely covered in the literature. First, there are the technical difficulties of the installation and as a result, errors in the positioning of an individual structure [56]. Many people believe that it is necessary to simplify the hardware shape to reduce the technical complexity of its positioning. Studies show that the proportion of perfectly positioned structures does not exceed 60%. At the same time, the question remains, what installation error is acceptable to maintain stability and subsequent good survival of the hardware [56].

Massive individual metal hardware does not always enable achieving osseointegration and biological fixation due to the insufficient contact area with the patient's viable bone and the imperfection of the microarchitectonics of the construction material. Therefore, it remains necessary to use additional osteogenesis stimulators to avoid joint instability in the long-term after surgery. Massive structures can injure the patient's bone tissue if its strength characteristics are reduced, and the surrounding soft tissues if the installation is inaccurate and there are protruding fragments [42, 57].

Difficulties are also presented by a detailed quantitative analysis of the bone defect, which is necessary to create an implant model and set the optimal direction for the fixation screws, considering the patient's bone density. The more complex the shape of the defect, the greater the error in quantitative analysis. In addition, this method is expensive and time-consuming for implant manufacture. However, with proper patient selection, careful preoperative planning, and well-performed surgery, the survival rate of such constructs is greater than 90% at 10 years or more after the surgery [43, 58].

Thus, hip arthroplasty in the presence of an acetabular defect is a complex surgical intervention with technical and technological aspects that have not been fully resolved since the choice of material for filling bone defects remains debatable. The goal of acetabular reconstruction is to restore its bone structure integrity for stable fixation of the endoprosthesis cup with joint rotation center restoration, and its proper functioning to increase the duration of implant survival. To date, there is no unified approach to solving this task set.

Morphological and clinical studies are required. Also, new osteoreplacement materials and technologies are needed to develop a unified surgical strategy that can improve the treatment results of patients with severe acetabular bone defects. The questions of acetabular defect classification, selection of optimal osteoreplacement material selection, the acetabular components themselves, and the their installation technique, depend on the specific clinical situation, remain open.

The variety of defect forms induces technical difficulties during the surgery and imposes increased requirements on the experience and skills of the surgeon, necessitating implant design simplification and using more regular geometric shapes. Significant difficulties in patient management are caused by the insufficient development of the legislative framework in applying individual structures, new materials, and techniques for restoring bone density.

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