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Review article

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Total ankle replacement

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Abstract

Introduction Total ankle replacement is definitely a tough issue for both orthopedic surgeons treating patients with ankle pathology and engineers who develop optimal implant constructs. Extreme short-time kinetic loads, complex motion biomechanics, anatomic features of the ankle result in high demands for ankle joint implants. In general, there is a positive tendency in an annual increase of the number of total ankle replacements. Alongside, a significant lagging in performing this procedure and the tendency for ankle arthrodesis has been observed in Russia. **Aim** To review the literature data about development and current status of total ankle replacement. To evaluate the use of modern implants for distal tibia replacement. **Material and methods** The given literature review includes analysis of foreign and domestic publications focused on issues of treatment of osteoarthritis of the ankle joint and tumors of the distal tibia. The information was searched for using GoogleScholar, PubMed, eLIBRARY, PubMedCentral in the Russian and English languages with the following keywords: total ankle replacement, ankle arthrodesis, ankle osteoarthritis, distal tibia replacement. **Discussion** Currently, there are controversies in selection of biomaterials and constructive parameters for ankle implants. Separately, there is an unsolved issue of selecting the optimal friction pair for bearing surfaces, as well as of operative technique features, such as implant fixation, surgical approach, modeling and restoration of the capsular-ligamentous complex. **Conclusion** Total ankle replacement is an effective alternative procedure to ankle arthrodesis and limb-sacrificing operations. To improve treatment results, optimal implant construction, fixation methods, selecting appropriate friction pair and capsular-ligamentous complex restoration should be further investigated in complex studies.

Keywords: total ankle replacement, ankle arthrodesis, ankle osteoarthritis, distal tibia replacement

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INTRODUCTION

Among a significant number of diseases of the ankle joint, undoubtedly, the leading place is occupied by a group of arthritis and arthrosis of various etiologies. Thus, in a large-scale study by Charles L. Saltzman et al. of 639 patients, the majority of cases (445 individuals) were patients with post-traumatic osteoarthritis (70 %), 76 patients (12 %) with rheumatoid arthritis and 46 cases (7 %) with idiopathic arthritis [1].

The general structure of the pathology of the distal tibia and ankle joint (AJ) consists of degenerative (arthrosis, arthritis of various etiologies, ankylosis) – 59 %, inflammatory (osteomyelitis of the leg and foot bones) – 7 %, hormonal (osteoporosis, secondary hyperparathyroidism) – 8 %, infectious (tuberculosis, alveococcosis) – 2 %, bone traumatic (consequences of injuries, fractures) – 22 % diseases. A separate group is patients with tumor lesions of the distal tibia and articular end (2 %). First of all, these are malignant neoplasms (osteosarcoma, chondrosarcoma, malignant chondroblastoma) – about 1 %, benign tumors (giant cell tumor, large chondromas causing significant destruction) – up to 3 %, secondary malignant neoplasms – 93 % and tumor-like diseases (bone marrow infarction, fibrous dysplasia) – no more than 3 % [2, 3].

While conducting this study, we often met with the question in the literature: "Arthrodesis or arthroplasty, which is better?" Already in the question itself, there is a definite challenge to a thorough study of this problem. Today, total ankle arthroplasty (TAA) is undoubtedly an excellent limb salvage alternative to ankle arthrodesis (AA), which for many years was the "gold standard" in the treatment of AJ osteoarthritis [1, 4, 5]. Every year, thousands of surgeries to replace AJ have been performed all over the world, and a large number of foreign studies have been devoted to the TAA results. This is facilitated by national registries of arthroplasties existing in Europe and America [4].

World statistics show the contradiction between these two methods of surgical treatment. At the same time, the summary indicators show cases of nonunion of fractures in patients after AA (13.7 %) and isolated cases of patients with TAA who required refixation due to nonunion after osteotomy of the medial malleolus. Similar situations have also been reported after arthrodesis of adjacent joints in TAA. Limb axis disorders are found in patients who have undergone AA (6.3 %) versus TAA (3.1 %). Infectious complications are observed in patients with AA in 6.1 % and in 3.4 % of patients after TAA. Fractures of the lower leg bones in the postoperative period were noted in 1.9 % of patients of the AA group and in 13.7 % of patients after TAA. Technical problems were observed after TAA operations (12.6 %), which included medial or lateral impingement, damage or wear of the polyethylene liner, failure and loosening of the implant. In general, the frequency of revision interventions averages 10.3 % for arthrodesis, and 20.5 % for ankle arthroplasty [5].

However, despite the increasing amount of scientific information on this issue, there is still insufficient systematized data on the long-term results of AJ arthroplasty. A recent meta-analysis by Yuhan et al. (2020) showed no statistically significant difference in the results of arthroplasty and arthrodesis. However, the need for further research and coverage of a larger amount of data has been stated to reliably answer the question of which of the techniques is preferable [6].

A different picture on this problem is emerging in Russia, where there is no arthroplasty registry and an extremely small number of TAA operations. Attention is drawn to the experience of colleagues from Krasnodar, who analyzed the results of 26 performed operations with a two-year follow-up period among whom two patients (7.7 %) had poor outcomes [7].

Mikhailov K.S. et al. (2018) report on the results of AJ arthroplasty in 71 patients divided into two groups. In the first year of follow-up, no signs of instability were found in any patient, within two years it was found in 6 patients out of 31 in the first group (19.4 %). When analyzing the long-term results of treatment, 16 patients (40 %) showed signs of aseptic loosening of the implant components. The seven-year survival rate in this study was 85.7 % [8].

Unfortunately, there is an obvious lag in the practical application of TAA in Russia in comparison with the experience of foreign colleagues, and the trend of arthrodesis as a method of choice remains [9].

Complex biomechanics of movements, extremely high and often extreme mechanical loads, anatomical features of the ankle joint structure impose the highest requirements on the design of the implants [10, 11, 12].

Currently, there are disagreements among design engineers in the choice of materials for the manufacture and design of implants. Separately, the issue of selecting the optimal materials for the friction pair of the articular surfaces, as well as the installation technique, remains unresolved [13, 14, 15]. Along with this, the features of the surgical technique, such as the method of fixation of implants in the bone bed, surgical approach, modeling and restoration of the capsular-ligamentous complex, are still the subject of discussion among orthopedic traumatologists dealing with ankle arthroplasty [16, 17].

Purpose To analyze the data of the world literature on the development and current state of ankle arthroplasty; to study the use of existong implants for lesions of the distal tibia 17].

MATERIAL AND METHODS

Our literature review analyzes foreign and domestic scientific publications dedicated to the treatment of osteoarthritis, tumor lesions of the ankle joint. Scientific publications over the past ten years were searched for in the electronic databases GoogleScholar, PubMed, eLIBRARY, PubMedCentral in Russian and English using the keywords "ankle arthroplasty", "ankle arthrodesis", "ankle osteoarthritis", "distal tibia arthroplasty". The review also includes current scientific publications on surgical anatomy and biomechanics of the ankle joint. The materials analyzed refer to 1973 through 2021 inclusive.

RESULTS

To comprehensively understand this problem and objectively assess the use of AJ arthroplasty, it is necessary to clearly know and take into account the anatomical features of the structure and biomechanical movements in the ankle joint [11, 12, 17–20].

The ankle joint is formed by the distal parts of both bones of the lower leg, the lateral and medial malleoli. Thus, the fibula and tibia form a horseshoe into which the talus enters. The talus block is part of it and has a wedge-shaped shape with somewhat wider anterior portion that the posterior one. It articulates with the tibia and fibula. In dorsiflexion, the anterior wider section of the wedge firmly engages in the fork, as a result of which the joint becomes very stable. On the contrary, in plantiflexion, the narrow posterior part of the talus block enters the ankle fork. Thus, significant joint mobility is possible (inversion-eversion movements). Based on this, a significant amount of injuries to the ankle joint occurs precisely in the position of plantiflexion [21].

The ankle joint capsule has three layers. The first layer is the capsule that contains the ankle ligaments; the second one are muscle tendons passing over the joint to the foot; the third one are fibrous bundles that hold the tendons at the site of their attachment to the bones of the foot [22].

The capsule, in turn, is divided into four sections. It is less strong in the anterior area, despite the fact that there are upper and lower retainers of the extensor tendons and a ligament connecting the anterior surface of the tibia and the neck of the talus. In the posterior part, the joint capsule is also weakened; the ligament is shorter here than the anterior one and stretches from the posterior edge of the tibia to the posterior aspect of the talus [11, 24].

However, the joint capsule has a stronger structure where the main ligaments are. From the medial side, these are bundles of the deltoid ligament, which are attached to the tibia (tibio-navicular section, anterior tibio-talus section, posterior tibio-talus section, tibio-calcaneal section); from the lateral side it is reinforced with the fibular ligaments (calcaneofibular ligament, anterior and posterior talofibular ligaments) [20, 26].

Between the lateral malleolus and the posterior tubercle of the talus (it is represented by a separate formation and is called the triangular bone) there is the posterior talofibular ligament, and the calcaneofibular ligament stretches from the lateral malleolus to the calcaneus [23]. Proximal to the lateral group of ligaments, the fibula is connected to the tibia by a number of strong fibers, which together form the so-called tibiofibular syndesmosis. This syndesmosis consists of an interosseous membrane that connects the tibia and fibula along their entire length. At the bottom, the membrane is reinforced with two thick fibrous bundles: the anterior inferior and posterior inferior tibiofibular ligaments [20, 27].

The medial ligament is called the deltoid. It is a single quadrangular structure, characterized in that it is the only one among the ligaments of the ankle joint that contains elastic tissue, which gives the ligament a certain degree of extensibility and, thereby, reduces the likelihood of rupture. The deltoid ligament consists of four bundles intertwined with each other and stretching from the medial ankle to the navicular bone, talus and calcaneus. The first bundle is the talonavicular ligament. Two more bundles go to the talus; one of them is called the anterior tibiotalar ligament, which is attached to the neck of the talus, the other is called the posterior tibiotalar ligament [24].

The talus, supported by those ligaments, moves together with the foot in true dorsal or plantar flexion, and together with the lower leg in pure inversion or eversion. An important ligament that is not part of the capsule, but is often affected in injuries of the ankle joint and the midfoot, is the spring ligament. This ligament stretches between the supporting structure of the talus and the navicular bone and closes the gap between the calcaneus and the navicular bone. Its function is to provide additional support to the head of the talus under the load of body weight. It consists of dense fibrous tissue, areas of which resemble articular cartilage [25].

Tendons are located above the capsule of the ankle joint, of which none, in fact, is attached to the joint itself, but all pass over it. All tendons are subdivided into two groups: extensors and flexors of the foot. The extensors run along the anterior surface of the ankle, and the flexors run posterior to the medial malleolus. There is a group of tendons of the fibula muscles passing behind the lateral malleolus. Those tendons are surrounded by synovial sheaths, the length of which reaches 8 cm. On the surface of the tendons, there are three diverging fibrous bands that keep the tendons from displacement. These bands are classified similarly to tendons. Accordingly, they are retainers of the extensors, flexors and tendons of the muscles of the fibula. The extensor retainer is divided into superior and inferior retainers. The flexor retainer consists of a single fibrous bundle passing behind the medial ankle. The peroneal retainer is divided into two, the superior and inferior tendon retainers of the fibular muscles [26, 27].

The analysis of foreign and domestic literature shows that the biomechanical features of the ankle motion are of particular importance.

It is possible to schematically depict the articulation in the ankle joint in a model consisting of two components: the lower part simulating the talus, on the upper part of which there is a cylindrical surface with a transverse axis of rotation; the upper part, representing the distal tibia and fibula, forms a single structure, which at the bottom has a cylindrical cavity corresponding to the cylindrical shape of the upper articular surface of the talus. The strong cylinder of the lower part is enclosed in the cylindrical cavity of the upper part and is held by its constituent bones [12, 28].

Directly in the ankle joint between the tibia and the talus, there is only one axis of movement: flexion and extension. In the neutral position, the sole of the foot is perpendicular to the axis of the lower leg. From this position, flexion in the ankle joint will be a movement that brings the rear of the foot closer to the anterior surface of the lower leg and ranges from 20 to 30 degrees. This movement is also called dorsiflexion. And, conversely, extension in the ankle joint (not quite the correct name – "plantar flexion") is a movement in which the dorsum of the foot moves away from the anterior surface of the lower leg, so that the longitudinal axis of the foot, as it were, continues the longitudinal axis of the lower leg, which is from 30 to 50 degrees.

At the final degrees of the motion, the ankle joint ceases to be the only active joint as the movements of the metatarsal joints are added. So, in extreme flexion, the metatarsal joints add several degrees, and the plantar arches are flattened. And, on the contrary, with extreme extension, an increase in the range is provided by an increase in the arches.

The range of flexion and extension is primarily determined by the size and the development of the articular surfaces. The articular surface of the tibia resembles an arc with a sector of 70°, and the block-shaped surface of the talus resembles an arc with a sector of 140–150°. Thus, that the total range of flexion and extension is from 70° to 80°. Since the “arc length” of the block-like surface is greater posteriorly than anteriorly, the range of extension is greater than that of flexion.

Ankle flexion is controlled by a number of factors:

1) Factor of bone contact. In extreme flexion, the upper surface of the talus neck contacts the anterior edge of the articular surface of the tibia, and if flexion continues, a fracture of the talus neck may occur. The anterior part of the joint capsule is not pinched between the two bones, because it is pulled up by the flexors, the insertions of which are attached to the capsule.

2) Factors of tension of the capsule and ligaments. The posterior part of the capsule is stretched, as are the posterior fibers of the collateral ligaments.

3) Muscle factor. The resistance exerted by the tonically active plantar and calf muscles usually limits flexion even before the above two factors come into action. Therefore, shortening of these muscles can lead to premature restriction of flexion, and the foot will be

permanently fixed in the extension position (equine foot).

Extension is controlled by similar factors:

1) Bone factors. The talus tubercles, especially the posterior ones, collide with the posterior edge of the articular surface of the tibia. Sometimes, in overextension, a fracture of the lateral tubercle may occur but its separation from the talus is more common; such a picture is called an accessory talus. However, the capsule is protected from pinching due to a mechanism identical to that which acts in flexion.

2) Factors of the capsule and ligaments tension. The anterior part of the capsule is stretched, as are the anterior bands of the collateral ligaments;

3) Muscle factor. The resistance exerted by tonically active flexors is the first limiting factor. Flexor hyperactivity leads to flexion contracture of the ankle joint (calcaneal foot) [29, 30].

The anteroposterior stability of the ankle joint and the correspondence of its articulating surfaces depend on the action of gravity, which presses the talus against the distal surface of the tibia. The anterior and posterior edges of the articular surface of the tibia form bony spurs that prevent the talus block from moving anteriorly, and more often posteriorly, since the foot in extension hits the ground very hard. Collateral ligaments passively participate in the co-optation of the articular surfaces. They are assisted by the muscles, which are active co-optators if the joint is intact. When flexion or extension exceeds normal limits, it means that one of the limiting factors is no longer working. Thus, in overextension, a posterior dislocation may occur associated with a partial or complete rupture of the capsule ligaments, or a fracture of the posterior edge of the tibia with a secondary posterior subluxation in the joint. Likewise, excessive flexion may result in an anterior dislocation or fracture of the anterior edge of the articular surface of the tibia. If the lateral collateral ligament is damaged, its anterior band is the first to suffer. If the damage is mild, it simply stretches, and it breaks if it is severe. If the centers of the arches do not coincide by 4–5 mm, it indicates a rupture of the anterior band of the lateral collateral ligament [31].

Transverse stability depends on the firm locking of its articular surfaces. Its structure is similar to the saddle joint, where the talus "saddle" firmly engages in the fork formed by the tibia and fibula. The two melleoli, like the two aspects of the forceps, grasp the talus on both sides if the distance between the lateral and medial malleolus does not change. This condition is only present when the malleoli and lower tibiofibular ligaments are intact. Strong lateral and medial collateral ligaments prevent the talus from rotating around its longitudinal axis.

The inter-malleolar forceps cease to function due to the rupture of the lower tibiofibular ligaments. It results in the expansion of the articular fork or diastasis in the ankle joint. The talus is no longer held tightly in the fork and moves from side to side. Injuries to the intermalleolar fork require treatment to restore the structure and functional integrity of the ankle joint [32]. This fact is of special consideration in total ankle arthroplasty (TAA).

Ankle joint arthrodesis

Undoubtedly, arthroplasty from both a bioengineering and clinical point of views is a promising operation to preserve movement in the ankle joint. Meanwhile, arthrodesis remains the most common method of surgical treatment of ankle joint pathology in many countries, including Russia. First of all, the cheapness and availability of this method in comparison with arthroplasty are complemented by pain relief in patients with terminal stages of crusarthrosis and extensive concomitant pathology, when arthroplasty is contraindicated or unsatisfactory functional outcome is predicted [33, 34].

Currently, there is a lot of variations in the ankle joint arthrodesis performance that differ in a number of technical points, including resection or preservation of articular surfaces, performing osteotomy in the ankle joint. The main difference is the choice of metal fixators. Pins, cannulated screws, intramedullary nails, plates and external fixation devices have been used as implants for arthrodesis. In some cases, a combination of different techniques is possible [35].

According to the summary data, the best functional results are obtained with cannulated screws as implants for arthrodesis of the ankle joint, with the help of which it is possible to achieve stable bone ankylosis and a minimum number of infectious complications. The use of intramedullary nails always leads to arthrodesis of the subtalar joint, what can be avoided with other techniques if this is not required [36].

A number of authors prefer to use the arthroscopic technique of arthrodesis, explaining the choice by a sparing attitude to the surrounding soft tissues and blood supply to the talus and tibia resulting in the reduction in the time of bone ankylosis. However, this version of the operation does not imply malleolus osteotomy [37].

Other researchers adhere to using an external fixation that enables to achieve bone fusion both with and without resection of the articular surfaces, correct severe deformity and provide compression in the postoperative period. However, the rate of infectious and inflammatory complications in the wire tracts remains high, and prolonged wearing of a bulky apparatus creates a number of inconveniences for patients [38].

The most common complication in arthrodesis is the formation of fibrous ankylosis and nonunion of the resection zone. In addition, among the conditions that worsen the prognosis and results of arthrodesis, there are obesity, diabetes mellitus, rheumatoid arthritis, and impaired blood supply to the distal lower leg.

The primary reasons of fibrous ankylosis in arthrodesis of the ankle joint are non-compliance of patients with the recommendations in the postoperative period and technical errors of the operation performance (insufficient removal of cartilage tissue, neglected deformity, instability of fixation, arthrodesis in a non-physiological position) [39].

Analysis of the literature showed frequent technical errors during surgical intervention (incomplete elimination of axial deformity, lack of sufficient stability and compression in the area of arthrodesis). The observed infectious complications in such patients do not depend on this indicator and are obviously associated with other reasons (severe rheumatoid arthritis, diabetes mellitus, instability of primary fixation with wires) [40].

Currently, in modern arthrodesis performance the choice of the method of ankle joint arthrodesis and the type of metal fixator depends not only on the type and severity of the deformity, but also on the patient's age, gender characteristics, diseases that contribute to unsatisfactory results (diabetes mellitus, severe rheumatoid arthritis degree, impaired blood supply to the distal tibia). We associate the best clinical and functional results both with fixation methods that ensure primary stability, and with regenerative and adaptive abilities, the presence of a compensatory stereotype of movements, constitutional features in patients, the absence of degenerative diseases of both large joints of the lower extremities, and joints of the mid- and forefoot. The most optimal modern implant for arthrodesis is cross-fixation with screws, which provides the greatest strength and good primary compression in the absence of pronounced impairment of blood supply to the articulating bones and radical removal of cartilaginous tissue [41]

Biomaterials in ankle joint arthroplasty

AJ implants must function in difficult conditions of cyclic loads and a potentially aggressive environment, but maintain the mechanical and chemical integrity of their components. In order to choose suitable materials for endoprostheses, the following main features are considered: biocompatibility, mechanical properties, economic costs of manufacturing. It is important to understand how the body reacts to the material and how the material behaves in a bioactive environment. Ideal materials will have high corrosion resistance, bone-like rigidity, and bioactivity only at the sites of the required fixation. The lower TAA survival rate relative to that of hip and knee arthroplasty is associated with the lack of optimal choice of materials specific to TAA, the rigidity of the conditions and the complexity of the joint geometry [13, 42].

On the modern market, there are many materials used for both the prosthesis itself and those used for a friction pair. Until now the question of the optimal combination remains open and debatable. Historically, the most used friction pair in joint endoprostheses has become "metal-polyethylene". However, the wear and biological activity of small particles of the components are pushing for the search and selection of new materials for TAA [14, 43].

An alloy of cobalt and chromium (CoCr) was first used in 1938 to replace the hip joint and is characterized by strength and resistance to corrosion and abrasion, as well as a good balance between mechanical properties and biocompatibility. This alloy shows good long-term results when paired with ultra-high molecular weight polyethylene (UHMWPE). The main limitation of CoCr is associated with metal ions formed due to performance associated with hypersensitivity and immune-inflammatory reactions [15, 44].

The problem of the release of metal ions was solved using a titanium base (Ti-6AL-4V) as the material of the endoprosthesis coated with a thin layer of titanium nitride TiN. This combination is close in its physical properties to the native bone. The limitation of this material is the potentially increased rate of component wear if the coating is damaged. A number of clinical studies have shown greater wear of polyethylene in combination with titanium nitride [42].

Ceramic is a good alternative to metal. As a material for the manufacture of implants, it is characterized by strength, a high degree of possible polishing and absolute biocompatibility. Having been used quite successfully in hip surgery, ceramics have a limited scope of application in TAA due to the complexity of the joint geometry and the need to use thin implant components, what increases the risk of its break. The only example of the real use of ceramics in TAA surgery is the TNK semi-constrained endoprosthesis (Kyocera, Japan) with a limited number of long-term results [16, 66].

Despite the rapid development and creation of biomaterials, UHMWPE remains preferred for the creation of implant components, especially in knee and ankle arthroplasty. It consists of long chains of ethylene and this configuration contributes to efficient load distribution. Modern materials made of ultra-high molecular weight polyethylene have good frictional characteristics when paired with metal, biocompatibility, and wear resistance [43].

Analysis of long-term results of TAA showed a relationship between periprosthetic osteolysis and wear products of UHMWPE. Histological examination showed the abundant presence of polyethylene wear particles both intracellularly and extracellularly [44]. To solve this problem, polyethylene with cross-linked molecules (UHMWPE) was created and introduced into the arthroplasty practice, the use of which leads to a significantly smaller amount of wear products. Moreover, the higher is the degree of crosslinking, the higher is wear resistance. UHMWPE with a high degree of crtoss-linking has shown significant wear advantages in hip arthroplasty [45].

TAA surgery typically uses moderately cross-linked UHMWPE. Analysis of modern data has shown the prospects for the use of polyethylene cross-linked with vitamin E in TAA surgery [46].

The survival of the implant is also determined by two types of stability. Primary stability is the initial mechanical fixation of the prosthesis obtained during surgery. It is achieved through precise press-fit placement of the component, the use of bone cement and, if necessary, fixation screws. Secondary stability is the subsequent biological fixation mainly due to porous coatings and bioactive materials on the implant surface [47]. Bone cement, which has been successfully used in hip and knee surgery, has not found wide application in AJ arthroplasty due to the limited possibilities for revision. However, it is noteworthy that all AJ implants in the United States are approved by the FDA only if cement fixation is used. In the Russian Federation and in other countris, an alternative method of fixation is the use of special coatings. In this case, secondary stability is achieved through osseointegration [48].

One of the ways to achieve osseointegration today is the use of a porous titanium coating. The cellular structure, achieved by plasma treatment of the metal surface of the component, allows bone tissue to grow into the free space and thereby ensure the stability of the endoprosthesis. One of the disadvantages of this fixation method is the potential risk of material fatigue at the interface [49].

The second main method of securing secondary stability is osseointegration through a hydroxyapatite (HA) coating. Both components, porous titanium and hydroxyapatite, have been frequently combined to achieve greater effect. Although both experimentally and theoretically the use of HA is encouraged, conclusive clinical data are still lacking. A number of studies have reported a large number of periprosthetic bone cysts when HA coatings were used [50]. This indicates the need for further high-quality studies of the effectiveness of HA in TAA surgery.

The newest method for fixing the components of AJ endoprosthesis is the use of a tantalum trabecular layer, which forms a porous structure similar in physical properties to cancellous bone. This layer is inert and resistant to corrosion; however, there is currently insufficient data to assess the effectiveness of the technique in TAA surgery [51].

Total ankle arthroplasty

The development of AJ arthroplasty began in the early 1970s, logically following the rapid development of hip and knee arthroplasty. The use of first-generation implants was unsuccessful: inadequate surgical technique, excessive bone resection, incongruence of articular surfaces, and inappropriate materials led to a high rate of complications and poor functional results. Lord and Marotte performed the first AJ arthroplasties using a reduced copy of the reverse femoral component for total hip arthroplasty. Arthrodesis of the subtalar joint was performed and the talar component made of polyethylene was implanted. Out of 25 cases of such an operation, only 7 patients had satisfactory results. That was the reason to reject this construction [52, 53].

Further evolution of TAA implants implied the transition to the anatomical shape of the components, minimal resection, the possibility of correcting deformities of the joint and foot, as well as the use of modern biocompatible and wear-resistant materials (Fig. 1).

Today there are many TAA implants that differ in their design parameters, conditions and indications for their installation. The variety and variability of technical and functional solutions are reflected in the diagram of T.S. Roukis and A.F.P. Bartel (2015) (Fig. 2).

Fig. 1 Photo of ankle prosthesis designs showing the fixation elements of the tibial and talus components

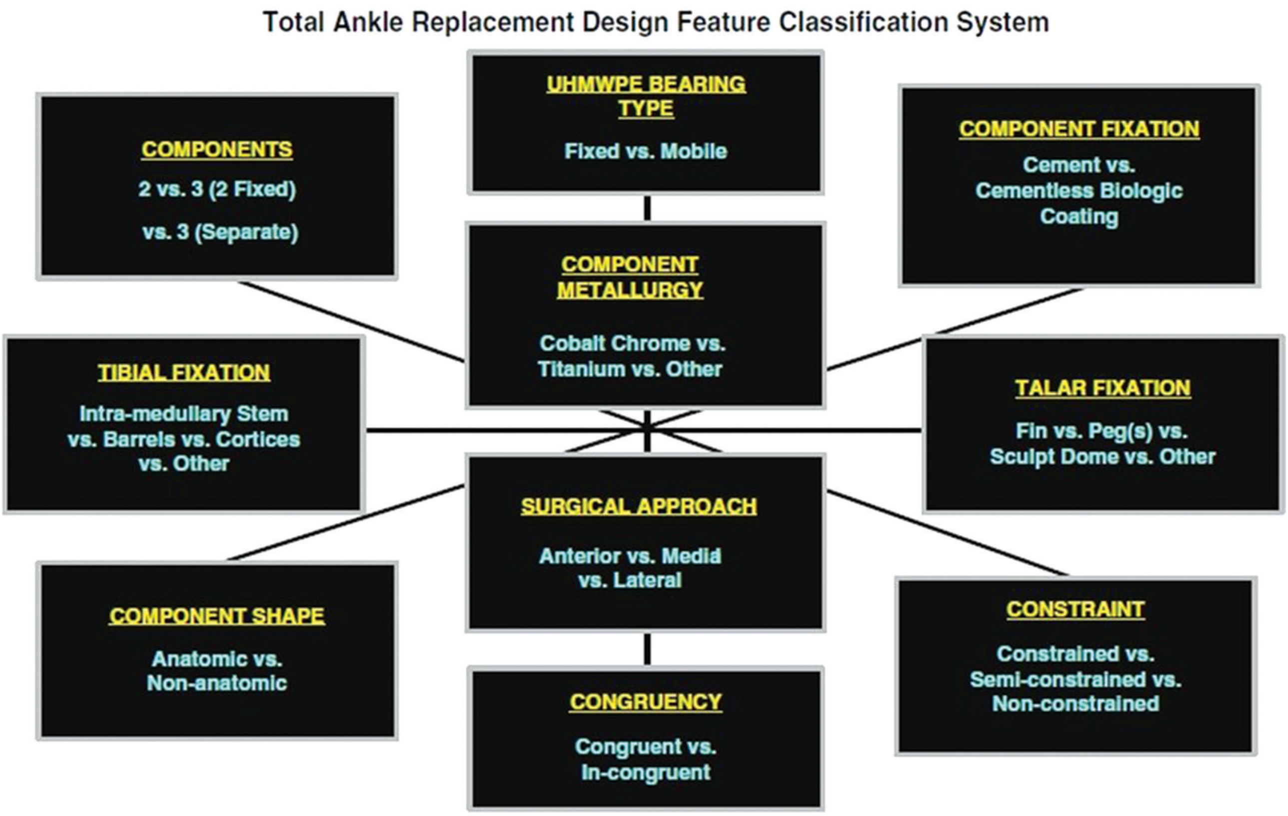

Fig. 2 Variability of technical and functional solutions in ankle arthroplasty

According to various sources, third-generation endoprostheses are currently relevant, characterized by non-constrained structure, cementless fixation of components and a polyethylene liner, either fixed-bearing or mobile-bearing. They provide an accurate reproduction of the anatomy of the native joint, adequate range of motion [54].

The INBONE ankle, developed in 2005, is a modular, cementless, two-piece system. The tibial and talar components made of plasma-treated porous titanium are assembled into a module and inserted into the tibial canal and talus sinus, respectively. This is the only endoprosthesis of a modular design at present. The implant is equipped with a fixed polyethylene insert. Harston et al. (2017) reported 149 cases of using the implant with a significant improvement in the function of the ankle joint and the elimination of pain. It was also reported that there was no difference in the results with preoperative valgus or varus deformity of the joint, what is a merit of this system and possible intraoperative angular correction. The survival rate of this endoprosthesis was 90.6 % at an average follow-up period of 5.9 years. Failure of the talar component was detected in 2.7 % of cases [55].

STAR ankle prosthesis, first developed in the early 1980s, has undergone significant design changes, and today more than 30,000 operations have been performed worldwide. This is a non-constrainedthree-component endoprosthesis, the tibial component of which is covered with hydroxyapatite, flat and fixed into the bone using two cylinders equidistant from the center. The talar component is domed and is anchored in the bone with a fin. A semi-cylindrical ridge is located in the center of the articular surface, which protects the liner from migration to the sides. The mobile polyethylene liner has a groove in the middle, congruent to the crest of the talar component, and a half-millimeter steel rim of X-ray marking. Palanca et al. (2018) reported a 73 % survival rate of cobalt-chromium components for a follow-up period of up to 15 years. In 70.7 % of cases, there were no changes in the position of the endoprosthesis components compared to the first postoperative radiographs. However, more than half of patients (52.4 %) with intact tibial and talus components required a second operation to replace the liner [56]. The study by Frigg et al. (2017) reported a 10-year follow-up of 46 patients. The implant survival rate was 94 %, but the replacement of components, including the liner, was required in 22 %. The 19-year survival rate was 91 %, but revision of one of the components was required in 45 % of cases. Analysis by Daniels et al. (2015) of 111 cases of using this endoprosthesis with an average follow-up of 9 years revealed 12 % of revision of the cobalt-chromium component, and there was a failure of the polyethylene liner in 18 % [57].

The HINTEGRA ankle, developed in 2000, is a third-generation non-constrained three-piece HSS endoprosthesis. Tibial and talar components made of cobalt-chromium, treated with plasma and coated with hydroxyapatite, are fixed cementlessly into the bone using pyramids with the possibility of additional fixation with screws. There are two variants of the implant, with a mobile or fixed polyethylene liner. Yang et al. (2019) reported the results of 210 arthroplasties in 205 patients with a mean follow-up of 6.4 years (2–13.4). The endoprosthesis survival rate was 91 % with 12 cases of poor results (5.7 %) [58]. Barg et al. (2013) analyzed 722 operations using this implant with an average follow-up of 6.3 years. The endoprosthesis survival rate was 94 % and 84 % after 5 and 10 years, respectively [59].

The trend of recent years is the development of fourth-generation endoprostheses, which is gaining momentum in the era of the integration of computer and engineering technologies into medicine. The use of new generation implants implies the use of patient-specific instruments and a personalized approach. An example of a promising project is the APEX 3D Total Ankle Replacement System. This is a three-piece, cemented endoprosthesis that offers placement options for both the right and left extremities. The tibial component is made of gradient porous titanium and has two anti-rotation rods on the proximal surface. The domed cobalt-chromium talar component has a complex articular surface geometry based on biomechanical study of a healthy joint during gait. The distal surface of the component is adapted to the morphologically altered bone structure in AJ osteoarthritis and is equipped with one anti-rotation rod [60].

Despite all the promising nature of the proposed prosthesis model, at present it is impossible to objectively assess the results of using this design due to the insufficient number of operations performed and the short follow-up period.

Ankle arthroplasty in oncological cases

Classical orthopedic arthroplasty has recently become a routine technique for reconstructing the ankle joint affected by injuries and degenerative disorders. Thus, it was possible to achieve satisfactory results and analyze complications in the immediate and long-term follow-up periods, and substantiate the revision surgery strategy [61].

Speaking about the surgical treatment of the pathology of the distal part of the tibia, it should be noted that for a long time, limb-sacrifying operations such as amputation or disarticulation served as an alternative to AJ arthroplasty in oncological cases [62].

The first literary references to the successful use of ankle endoprostheses in bone oncology were published in 1999 by S.H. Lee et al. [63].

A similar report was shared by colleagues at the Royal Orthopedic Hospital in Birmingham that same year. The clinical series included five patients who refused amputation. The median age was 32 years. Two had osteosarcoma, the rest three had Ewing's sarcoma, leiomyosarcoma, and a giant cell tumor. The prostheses were custom-made based on the expected level of tibial resection. The stem and body of the tibial component were made of titanium. The talar component was made of a cobalt chromium alloy of an ultra-high molecular weight polyethylene liner. The prosthesis was designed as a hinged semi-constrained, the fixation of the prosthesis components in the bone was cemented. In the postoperative period, bed rest was indicated for 5 days, as well as plaster immobilization without weight-bearing for 6 weeks, dosed loading after plaster cast removal (Fig. 3). All patients achieved full limb weight-bearing by 3 months. Two deaths were recorded in that series due to the progression of the disease. Local relapse was found in one patient, wound necrosis and deep infection developed in one patient, and there was aseptic loosening of the talar component, damage to the distal fibula and severe chronic pain in one patient. The functional assessment in the presented cases ranged from 50 to 90 % (average 65 %) [64].

Fig. 3 X-ray of the ankle of a patient with chondromyxoid fibroma. Condition after arthroplasty with an oncological prosthesis (2 months after surgery) [64]

In 2009, a team of authors at the Royal National Orthopedic Hospital (Stanmore, Middlesex, England) reported the results of six patients treated between 1981 and 2007. They used endoprostheses of their own design which were custom-made (Stanmore Implants Worldwide, Center for Biomedical Engineering, London, UK) using computer-aided design and manufacturing technology (CAD-CAM). It has a connected construct to mimic the stability normally provided by the ankle capsule and its ligaments, what are often sacrificed by tumor removal. The prosthesis consists of two components, tibial and talar, and has a liner made of ultra-high molecular weight polyethylene of high strength on the tibial component. The latter is made of titanium alloy (TA1) with a grooved intramedullary nail for cement fixation, in the proximal tibia, a hydroxyapatite (HA) collar to promote bone ingrowth. The distal tibial component has a nitrided surface to prevent surface wear with subcutaneous accumulation of wear particles. The talus component, made from a cobalt-chromium-molybdenum alloy (ASTM F75), is secured to the bone with one or two flanges (Fig. 4).

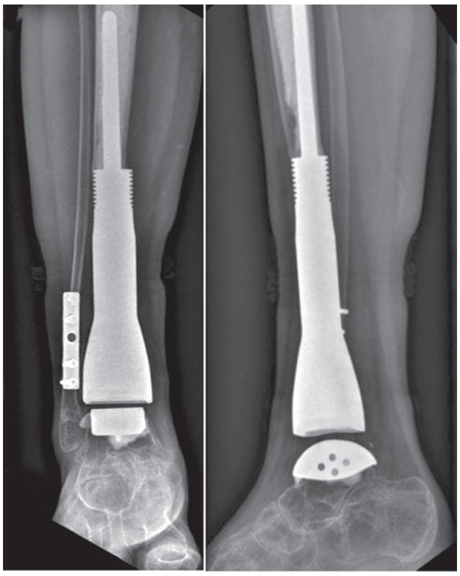

Fig. 4 Radiographs of the ankle. Condition after arthroplasty with an oncological prosthesis (19 months after surgery) [65]

No oncological complications were reported in that study. Two out of six patients underwent transtibial amputation due to chronic infection, and four patients who retained the endoprostheses had an average MSTS score of 70 % [65].

In 2011, doctors from the Orthopedic Surgery Department of the Japanese Medical Center for Cancer and Cardiovascular Diseases shared their experience of managing two cases of oncological endoprosthetics for tumors of the distal tibia. One patient had metastatic lesions due to colon cancer and the second had low-grade central osteosarcoma.

The prosthetic system (Japan Medical Materials Ltd., Kyoto, Japan) was custom-made based on the expected level of tibial resection for its distal tumors. The prosthesis manufacture took about 6 weeks. The component was made of a titanium (Ti – 6Al – 4V alloy) for an intramedullary rod and an alumina ceramic body. The articular surface of the epiphysis was is coated with ultra-high molecular weight polyethylene (UMWP) to achieve smooth contact with the articular surface of the talus (Fig. 5).

The patients followed bed rest for two days and immobilization with a short plaster cast for four weeks. Partial load on the leg and passive and active movements were allowed after its removal. After about 6 weeks, full leg loading was allowed. One of the patients subsequently developed a local recurrence in the distal fibula. Resection was performed 8 months after the primary surgery, no signs of progression were observed. The ankle dorsiflexion range was 10° and plantiflexion 30°. The average MSTS functional score was 83.3 %. The second patient had a fibular fracture intraoperatively and was fixed with a intramedullary wire. The range of dorsiflexion of the ankle joint after surgery was 5 °, plantiflexion was 30°. The patient remained disease-free at the last follow-up and showed no radiographic attenuation or subsidence of the talar component for eight years. The functional score on the MSTS scale was 80 % [66].

In Russia, an ankle joint endoprosthesis for lesions of the distal metaepiphysis of the tibia was first used in 2008 at the Blokhin Center for oncology, which was later reported by M.D. Aliev [67].

Primary tumors of the distal metaepiphysis of the tibia are quite rare, therefore there are certain difficulties and gaps in the objective assessment of the results in oncological arthroplasty [62].

Currently, in our country, there is little information a on the experience of arthroplasty with oncological ankle prostheses and only in leading federal institutions [67, 68].

Fig. 5 Radiographs of the ankle joint of a patient with poorly differentiated central osteosarcoma. Intraoperative fibula fracture. Condition after arthroplasty with an oncological prosthesis (3 months after surgery) [66]

The most recent publication on the experience of oncological endoprosthesis of the ankle joint was the work of a team of authors from the Blokhin and Herzen institutes under the guidance of the academician of the Russian Academy of Sciences M.D. Aliev. It deals with the results of treatment of 20 patients with benign bone tumors and primary localized bone sarcomas in the period from 2008 to 2019. The surgeons performed 33 operations (primary and revision arthroplasty) for lesions of the distal epiphysis of the tibia. Two types of constrained total oncological endoprostheses of the ankle joint were used. First were implants from Prospon (Czech Republic), a block type in which the metal part is made of titanium alloy TiA16V4 and coated with carbon. The plastic elements of the endoprosthesis unit are represented by 2 sleeves made of polyetheretherketone (PEEK). The assembly shaft is installed separately and fixed through its block. The shape of the tibial and talar parts of the endoprosthesis is cylindrical, alloy material TiA16V4. In the second case, the surgeons used German oncoprostheses from Implantcast, the design of which implies a block type. The metal part of the endoprosthesis assembly is made of CoCrMo alloy. The plastic elements of the endoprosthesis unit are represented by 2 sleeves made of high molecular weight polyethylene UHMW-PE, they are installed directly on the unit shaft, which is fixed to the talar component of the endoprosthesis, and then is implanted into the tibial module of the ankle unit of the endoprosthesis. The tibial stem has a hexagon shape to ensure rotational stability, the talar component is cylindrical. Both stems are made of CoCrMo alloy. The main complication in this study was aseptic instability in 46.2 % of cases. Oncological complications were detected in 45 % (of which local recurrence was 15 %). However, the average functional outcome after ankle arthroplasty was 76 % on the MSTS scale [69].

The authors agreed in the conclusion that this direction has significant potential in the treatment of benign and malignant lesions of the distal segment of the tibia. The number of relapses and the rate of complications directly depend on the choice of the endoprosthesis model, and namely, its design, construction of the endoprosthesis units, methods of fixation, materials used, and compliance with the principle of oncological radicality.

DISCUSSION

Despite the fact that TAA has become a generally accepted method of treatment of end-stage AJ osteoarthritis along with arthrodesis, the rate of revision interventions is significantly higher than after arthrodesis. Patients undergoing TAA report better functional results in terms of preservation of gait kinematics and range of motion than after ankle arthrodesis. Based on a review of the current literature, TAA is effective in treating pain and restoring function. However, in order to achieve the best results, a detailed approach should be undertaken for selecting patients for this operation. Also, an important aspect is the economic component of the operations. Arthrodesis is much cheaper and better in terms of treating pain, however, the volume of motion, obviously, has to be sacrificed. In addition, the gait kinematics is disturbed. After TAA, the volume of AJ movements is retained and improved.

Although there is definite evidence to date in favor of TAA for maintaining range of motion, reducing pain and high satisfaction with treatment, the percentage of revisions significantly exceeds that after arthrodesis. Moreover, there is concern about the long-term risks of osteoarthritis in the adjacent foot joints (talonavicular, calcaneal and/or subtalar) after arthrodesis. When considering other treatment parameters, TAA is an attractive alternative for the treatment of AJ OA and maintaining joint motion. However, to date, there is insufficient long-term evidence to confidently recommend TAA over arthrodesis for all patients.

The analysis of the world literature showed the trends in the ankle arthroplasty, and also revealed a number of unresolved issues in this promising and actively developing direction. A separate branch of this issue is oncological arthroplasty of the distal tibia and ankle joint. Up to date, there is no single concept due to the insufficient amount of systematized data and the small number of described cases. However, according to the literature, there is no doubt about the relevance of this direction and the search for unified approvals of medical engineering and practical orthopedics.

CONCLUSION

1. Standard ankle joint replacement is an effective alternative to arthrodesis. The use of modern implants based on evolving anatomical and personalized technologies enables to achieve positive immediate and long-term results in the overwhelming majority of cases (92.3 %).

2. Despite a good state of the issue all over the world and the annual increase in the number of TAA, there is still insufficient data to assess the long-term results of treatment. In Russia, there is a noticeable lag behind Europe and the United States in this direction, which complicates the creation of a domestic evidence base for this type of treatment, requires the development of this direction and the creation of up-to-date registries.

3. Oncological TAA is undoubtedly a direct alternative to limb-sacrifying operations for tumor lesions of the distal tibia, accompanied by a large number of complications (up to 40 %). To improve the results, further comprehensive research is needed to develop the optimal design of the prosthesis, implant fixation methods, selection of a suitable friction pair and the reconstruction of the capsular-ligamentous apparatus.

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