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RADIOLOGICAL DIAGNOSIS OF HIP JOINT ABNORMALITIES IN CHILDREN

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Abnormalities of the hip joint in children are caused by a wide range of diseases, including both congenital and acquired types. Hip dysplasia, Legg–Calve–Perthes disease, and juvenile slipped capital femoral epiphysis account for up to 25% of all diseases of the musculoskeletal system in pediatric patients. The early diagnosis of these disorders and timely treatment are critical for the prevention of childhood disabilities.

Keywords: hip joint disorders, diagnostic methods, children.

Hip joint pathology in children encompasses a wide range of diseases, including congenital and acquired disorders [1]. Hip dysplasia, Legg–Calve–Perthes disease, and juvenile slipped capital femoral epiphysis account for up to 25% of all pathologies of the musculoskeletal system in pediatric patients. The early diagnosis and timely treatment of these diseases are of paramount importance to prevent disabilities in children [2–6]. The diagnosis of hip joint pathology in children is a topical issue. The problem is particularly acute for children with hip dysplasia and Legg–Calve–Perthes disease because treatment outcomes depend directly on the time of diagnosis [7–10].

The range of available diagnostic capabilities to detect hip joint pathology has significantly extended. Existing diagnostic techniques have greatly improved and now yield significantly more information. Minimally invasive techniques have also been developed [11]. Anamnestic and clinical diagnostic methods are supplemented with laboratory [12] and instrumental methods [13, 14, 15] such as X-ray imaging, computed tomography (CT), multispiral computed tomography (MSCT), magnetic resonance imaging (MRI), ultrasonography (USG), and radiothermometry.

USG is a basic technique used in Russia and other countries to diagnose hip dysplasia in newborns because it is noninvasive, readily available, and enables the administration of multiple examinations to the same patient [16–22]. USG diagnosis is used to analyze opaque structures such as cartilage, joint capsules, muscles, and tendons, which are the main constituents of the hip joints in infants. This method avoids the adverse effects of radiation, including the gonadal dose due to X-ray examination of the hip joints [23, 24, 25]. Hip USG, according to the method of R. Graf, is an efficient screening method in early neonates. In most cases, USG visualizes well-developed joints during the first days of life, even in the presence of hip dysplasia. The percentage of inconsistency between the clinical presentation of hip joint pathology and the results of USG is 41%, mainly biased toward overdiagnosis based on clinical examination [26].

The proportion of delayed diagnosis in children is very high despite the large number of studies designed for this purpose [27]. Therefore, we require a well-defined system of early diagnosis of hip dysplasia that must be achieved through the development and implementation of diagnostic and treatment standards. Presently, mass orthopedic screening of newborns at a maternity clinic using hip joint USG identifies well-developed hip joints, enables early diagnosis and treatment of hip dysplasia, and detects potentially troublesome joints that require further compulsory ultrasound (US) monitoring. Postnatal orthopedic screening of infants, including the use of hip joint USG, is not performed in Russia because an infant's initial visit

often occurs between the ages of 3 to 6 months [9]. Physicians in some countries conduct compulsory examinations of newborns, including clinical examinations and USG [28, 29]. For example, the Austrian and German healthcare systems employ mass screening, although healthcare systems of Europe, Australia, the United States, and some countries in Asia employ selective screening [21, 22, 30]. The use of USG to screen the general population is widely discussed. Although high cost is a disadvantage [31], some researchers endorse mass US screening [10, 32].

Numerous studies do not show significant differences between the efficacies of general and selective US screening, including the detection of degenerative changes in adult patients [33, 34]. However, the importance of US screening is undeniable because general and selective examinations reduce the requirement for surgery [37]. The algorithm used to diagnose hip dysplasia in infants younger than 3 months includes clinical and functional parameters as well as USG examination. The diagnostic algorithm applied to children older than 3 months includes clinical, functional, and imaging examinations such as hip joint X-ray, US examination of the cervical and lumbosacral spine, and duplex scanning of lower extremity vessels [36].

Physicians in Russia recently began performing lateral US screening examinations of hip joints in infants. According to A.B. Gurevich, a comprehensive US examination of patients with hip joint dysplasias should include lateral and anterior approaches supplemented with the assessment of regional hemodynamics. The inability to acquire a single image of the femoral head, neck, and shaft on a single USG section is an important diagnostic criterion of torsional changes in the femoral neck [16]. Doppler US examination assesses vascular changes in the hip joint and is particularly valuable for examining newborns and infants due to advantages such as information content, noninvasive administration, rapid examination, bedside use, and multiple examinations. Doppler sonography supplements the primary diagnosis of pathology and continuously monitors treatment [16]. M.S. Kamenskikh et al. proposed a diagnostic method using USG data for hip dysplasia in infants younger than three months [37], which is based on determining the value of the acetabular angle and the degree of femoral head penetration into the acetabulum, which significantly reduces whole-body exposure to radiation.

Evidence indicates the possibility of using real-time USG of the femoral head to assess joint stability, and USG diagnosis was suggested to differentiate congenital dysplasia from inflammatory joint diseases in young children [5]. International comparative studies of the results of US and X-ray examinations of children aged 4 to 50 weeks with suspected hip dysplasia show that USG is a more accurate diagnostic method [20]. According to O. Yu. Litnetskaya, the US examination of hip joints is the only diagnostic method that differentiates low-grade dysplasia and hip joint immaturity [38]. For example, immaturity was diagnosed in 36.84% of children with symptoms of low-grade dysplasia who consulted a physician [38].

The optimal age of a child suitable for US examination is a controversial subject. According to A. G. Baindurashvili et al., US screening of the musculoskeletal system of newborns should be conducted at a maternity hospital [39]. According to Yu. I. Lozovskaya, if clinical signs indicating hip joint pathology are detected in an infant during this time, a US examination is recommended within the first 10 days of life [11]. I. Yu. Chukhraeva believes that US screening performed at maternity hospitals is efficient for well-developed hip joints. In other cases, the objective evaluation of long-term outcomes is not possible. Children with Graf type Ia and Ib joints detected at maternity hospitals do not require further regular monitoring. Type IIa hip joints are subject to monitoring because they are potentially susceptible to the subsequent development of dysplasia [26]. According to the American Academy of Pediatrics and others, US examination should be performed after infants reach the age of 4–6 weeks to avoid false-positive US results, which prevents unnecessary treatment in many newborns [40, 41, 42]. The reason for this recommendation is that false-positive US results for a physiologically immature neonate pose a significant problem because mild dysplasia diagnosed in some patients using USG during the first month of life is not subsequently confirmed [43, 44].

Follow-up US monitoring is indicated for children with Graf type IIa joints. For these patients, re-examination aimed at assessing the disease course is advisable at 1 and 3 months. If the angular parameters of osseous coverage worsen

at the age of 1 month, orthopedic treatment is indicated. If Graf type IIb hips with US signs of delayed ossification of the cartilaginous region of the acetabular roof are detected at the age of 3 months, further monitoring is indicated. If there are no US signs of delayed ossification of the cartilaginous region of the acetabular roof, orthopedic treatment is indicated. Children with Graf type Ia and Ib hips are excluded from follow-up, regardless of the stage. X-ray examination of the hip joint to control the progression of hip dysplasia or to select the optimal subsequent treatment should be implemented for children older than 3 months [26].

According to A.B. Gurevich and K.V. Vatolin, a comprehensive US examination includes grayscale scanning, color and power Doppler mapping, and pulsed wave Doppler. For children younger than 1 year, US examination is performed in the B-mode starting with the standard Graf method. The anterior approach is then used, which is accepted for older children and adults. X-ray-transparent structures and structures surrounding the hip head are assessed in the B-mode. The quantitative and qualitative evaluations of circumflex femoral vessels and vessels feeding the femoral head, round ligament of the femoral head, and proximal femur are conducted after the assessment of anatomical structures. The diameters of the circumflex femoral vessels are measured using the power Doppler mapping mode. The analyzed indicators are as follows: number of circumflex vessels, systolic and diastolic blood flow, and index of resistance. The same approach is used to assess vessels feeding the neck and head of the femur as well as the vessels of the joint capsule [45].

S.R. Teixeira et al. [48] evaluated the possibility of using the pubo-femoral distance (PFD) as a simple tool for detecting dysplasia in newborns and found that the sensitivity, specificity, and accuracy of PFD were 94.4%, 93.4%, and 97.2% at the neutral position and 94.4%, 89.0%, and 95.5% with the hip flexed, respectively. Further, PFD can be used as a highly accurate screening tool for the diagnosis of hip dysplasia, regardless of the expertise of the radiologist [28]. This method is used with USG to diagnose hip dysplasia and to assess spatial relationships in the hip joint after the closed reduction of the hip. USG described by van Douveren [46] is executed in the transverse plane. A sonographic section extends through the superior pubic ramus, acetabulum, and femoral head and neck. Successful reduction aligns these anatomical landmarks. If the line passing through the femur passes behind the pubic bone line, reduction is not achieved and cannot be evaluated using X-ray imaging in the presence of the posterior displacement of the femoral head. The advantages of this method include its high reproducibility and accuracy. USG is invaluable for diagnosing hip joint disorders such as *juvenile slipped capital femoral epiphysis* (JSCFE) and Legg-Calve-Perthes disease. USG enables an earlier diagnosis of JSCFE than conventional radiography, and USG differentiates between stable and unstable JSCFE [32]. Imaging techniques such as bone scanning that reveal bone viability are particularly important for patients with aseptic necrosis [19]. For example, the distribution of radioisotopes is determined using a gamma detector. The ability of this method to detect functional rather than structural changes contributes to its sensitivity [24].

Because vascular disorders are the main cause of the disease, the assessment of blood circulation in this area using noninvasive techniques is a topical issue. Dynamic Doppler USG provides a reliable assessment of the vascularization of the hip joint area as well as the dynamic control of changes in the femoral head structure and blood flow. USG is an informative and noninvasive method for examining children with hip joint disorders associated with Perthes disease and can be used for early diagnosis, follow-up, and evaluation of treatment efficacy with the possibility to correct remedial measures. The sonographic signs of Perthes disease include the effusion of the anterior joint (neck area), thickening of the femoral head cartilage, thickening of the synovial membrane, and deformation and fragmentation of the ossification center of the femoral head with persistent joint cavity effusion. These findings are typical for early and late stages of the disease, including the fragmentation stage. US examination determines the affected site of the femoral head in the area of the anterior surface of the femoral head, its upper pole, and the lateral region of the epiphysis. The progressive course of the disease is sonographically characterized by a reduced distance between the anterior *acetabular edge* and femoral metaphysis and deformation of the femoral head with the loss of its height compared with the uninvolved side.

During treatment, USG images change, including a reduction in joint cavity effusion and

normalization of the thickness and structure of the femoral head cartilage. The formation of a clear line by the subchondral bone and normalization of the USG image of the hip joint are visualized during repair, which is clinically manifested as functional recovery of an affected hip joint [47]. However, US examination does not exclude performing X-ray imaging of the hip joints because US does not provide an overall assessment of the shape of the epiphysis and does not reveal the relationship between the femoral head and acetabulum [12]. X-ray CT, particularly multislice CT, significantly extends the diagnostic capabilities of the analysis of hip joint pathology [13] and is the method of choice for imaging primary and secondary ossification centers [48].

MSCT facilitates the assessment of the osseous structure and visualization of growth plates and the primary and secondary ossification centers of joints. Furthermore, it assesses the spatial orientation of the hip joint components, displacement pattern of bone fragments in traumatic injuries, localization of a bone lesion, and extent of involvement of adjacent anatomical structures. Contrast enhancement (particularly the double contrast technique) significantly extends the capabilities of the method because it assesses the state of the cartilage and soft tissue structures of the joint, which is most important in young children [49]. Further, the diagnosis of pathological changes in the joint using contrast-enhanced CT accurately represents the arrangement of all structures of the joint in high dislocation of the femoral head [14].

Further, MRI is the method of choice for imaging the cartilage and soft tissue structures of the hip joint. According to E.V. Ogarev, combined plain radiography and double-contrast CT can be used as an alternative method that enables the visualization of the cartilage and soft tissue structures of the hip joint [48]. MRI of children is the most widely used imaging technique for diagnosing and planning the treatment of Legg–Calve–Perthes disease, congenital hip dislocation, and dysplastic coxarthrosis [15, 25, 40, 50]. Thus, the MSCT and MRI analyses of children with congenital hip dislocation reveal qualitative and quantitative changes in the hip joint and detect anatomical changes revealed by X-ray imaging in the hip joint associated with the patient's age and the number of surgical interventions, which significantly impact the prognosis of long-term treatment [13, 15]. MRI is the most informative method available to assess avascular necrosis. Plain radiographs do not reveal avascular necrosis for several weeks or months. After this time, radiographs detect patchy flattening of the structure of the affected bone area with an arcuate lucency. A subchondral crescent sign subsequently appears, and a fracture or flattening of the affected bone appears. A later stage of medullary necrosis is characterized by serpentine calcifications. Bone scans administered during the early stage reveal hypofixation of the radioisotope in the affected area that returns to hyperfixation caused by repair after weeks or months. Moreover, MRI is the most sensitive method for detecting avascular necrosis [55].

Methods to detect aseptic necrosis depend on the localization of the lesion. When studying aseptic necrosis of the femoral head, images of both femoral heads should be obtained using a continuous-phase imaging coil. Frontal and sagittal sections representing the subchondral bone tissue are better compared with axial sections and are therefore preferred for this examination. T1- and T2-weighted pulse sequences (PSs) are usually sufficient to establish diagnosis. Short tau inversion recovery and T2-weighted fast spin echo with the suppression of signals emitted by fat are used as well because of their high sensitivity for detecting bone marrow edema. Contrast enhancement facilitates the assessment of residual vascularization or revascularization in patients with aseptic necrosis and detects fluid accumulation.

Characteristic MRI signs:

- images obtained during the first 5 days demonstrate reduced intensity of the T1-weighted signal and increased intensity of the T2-weighted signal due to bone marrow edema. Joint cavity effusion is often observed, which serves as an indirect indication of avascular necrosis;
- MRI signal parameters of the necrotic area become increasingly heterogeneous at a late stage;
- condensed bone lesions detected on plain radiographs are characterized by decreased signal intensity of T2-weighted images. Necrotic patches may be surrounded by a rim of edema with a high-intensity T2-weighted signal. This zone of reactive edema corresponds to early revascularization and increased intraosseous pressure and should be considered part of the necrotic area;

– contrast-enhanced T1-weighted PS may help assess the residual perfusion or revascularization of the necrotic area. The lack of contrast enhancement indicates necrosis, and an increased signal in the necrotic area may indicate the remaining viable tissue or sites of edema.

The Ficat and Arlet classification (1980) is widely used to determine the stage of avascular necrosis as follows:

Stage 1. Decreased signal intensity, sometimes a single line, is observed in T1-weighted images. A double-line sign with increased signal intensity may be observed on T2-weighted imaging.

Stage 2. MRI morphology is similar to that of Stage 1, but a modified signal is often wedge-shaped and clearly demarcated. Necrotic bone tissue is histologically demarcated by reactive granulation tissue.

Stage 3. The femoral head is deformed due to the flattening of subchondral bone tissue. A crescent sign is observed in X-ray images.

Stage 4. Progression of head deformity and flattening of the subchondral bone. Cartilage destruction and progressive joint space narrowing are observed.

MRI can diagnose early-stage Perthes disease. T1-weighted images that show a hypointense signal from the femoral head, and sometimes on T2-weighted images depending on the degree of osteosclerosis, serve as the typical MRI sign. Concomitant joint cavity effusion is often observed.

JSCFE is diagnosed using X-ray imaging, which is more useful than MRI. However, MRI may help detect concomitant osteonecrosis of the femoral head. The frontal plane is the best choice for assessing the femoral head epiphysis.

USG and X-ray imaging may solve all diagnostic questions in children with complex dysplastic changes of the hip joint. The advantages of MRI are as follows:

– provides images in many planes;
– provides more accurate assessment of the position of the cartilaginous femoral head;
– provides for the examination of the hip joint in a plaster splint for a gantry tunnel with an appropriate diameter;
– excludes exposure of the patient to radiation;
– detects avascular necrosis of the femoral head at early stages.

Hip joint images are acquired in the frontal and axial planes using T2-weighted PS and specific PSs for cartilage imaging.

MSCT with multiplanar reconstruction is highly informative because it determines the geometric relationships in the hip joint and identifies abnormal spatial relationships with a greater precision [11]. Moreover, MSCT performed for special indications estimates angular parameters in the axial and sagittal planes as well as the standard X-ray parameters. The reconstruction mode in three dimensions assesses in detail the spatial relationships in the hip joint. The indications for MSCT are as follows: 1. irreducible dislocation or subluxation of the femoral head during treatment to identify obstacles and evaluate the torsion component, 2. late diagnosis of dislocation or subluxation of the femoral head to visualize joint structures in three dimensions, 3. residual dislocation or subluxation in older children to assess decentralization and torsion events and the detection of cystic changes in the *neoacetabulum* and degenerative changes in the joint structures [16].

MRI plays an important role in the diagnosis and assessment of joint morphometric parameters that determine the development of coxarthrosis. According to O. Yu. Blishch, the structural variants of hip joints characterized by a neck-shaft angle of > 133° and an acetabular index of > 8° account for the high risk of osteoarthritis of the hip in these patients and an increased probability of an aggressive course of the disease. Moreover, MRI plays an important role when diagnosis is difficult and can assess damage to the cartilage and the risk of avascular necrosis [29].

The articular cartilage is the complex, heterogeneous, and mechanically anisotropic tissue that mainly comprises a three-dimensional network of collagen, proteoglycans, and water. MRI is the gold standard for the noninvasive examination of this tissue and provides information on structure, morphology, and molecular composition. Methods are available to assess the morphological and biochemical characteristics of the articular cartilage. For example, delayed gadolinium-enhanced MRI of cartilage is a relatively new and promising method that quantifies the articular hyaline cartilage by measuring the loss of glycosaminoglycans (GAGs). Combined with a paramagnetic contrast agent with negatively charged molecules (Gd-$[DTPA]^{2-}$), the distribution of GAGs in the cartilaginous matrix is inversely proportional to the concentration of

negatively charged GAGs. Therefore, the highest Gd-$[DTPA]^{2-}$ concentrations occur in areas with the lowest GAG concentrations

Because of its long history of use, X-ray examination of the hip joints is the major method used in Russia and includes arthropneumography. Radiographs and arthropneumographs are used for the comprehensive indexing of hip joints, which are required to obtain a complete picture of joint structures and to predict their further development. These techniques evaluate the spatial relationship of the pelvic and femoral components of the joint, size and shape of the acetabulum and femoral head, relationships in the hip joint, bone structure of the acetabulum and femoral head and neck, condition of the Y-shaped cartilage and metaepiphyseal growth plate, and the degree of ossification of the femoral head [51].

The most widely parameters used for X-ray diagnosis are as follows: acetabular index, defects of the lateral acetabular edge, lateral and/or proximal displacement of the femoral head, and discontinuity of the Shenton–Menard arch [52]. A method for determining the degree of the anterior coverage of the femoral head using X-ray imaging in the Lequesne and de Seze view is performed with the patient lying (standing), and the frontal pelvic plane is rotated 65° relative to the screen. The lower extremity is placed in the neutral position at a distance of 100 cm, and the beam is centered on the femoral head. Radiography in this projection allows the assessment of the anterior acetabular coverage of the femoral head by measuring the angle of the anterior femoral coverage between the rays rising vertically from the femoral head center to the point of the anterolateral acetabular edge, which is normally 18–30°.

However, it is impossible to use this method to evaluate a severe femoral head deformity because it is difficult to determine the head center. Therefore, a method proposed by C. Etsuo et al. is used to assess anterior femoral head coverage. Three vertical lines are drawn on an oblique radiograph to assess the anterior coverage. The first line is drawn vertically through the medial edge of the femoral head, the second line is drawn through the lateral acetabular edge, and a third line is drawn through the lateral edge of the femoral head. The distance between the first and second lines is defined as parameter A, and the distance between the first and third lines is defined as parameter B. The degree of coverage is calculated as follows: $A/B \times 100$. The mean normal values are $81.7 \pm 4.6\%$ and $88.5 \pm 6.6\%$ for girls and boys, respectively in boys.

Artificial contrast enhancement visualizes the cartilaginous and soft tissue structures of the hip joint, and when applied to the hip joint cavities of children and adolescents, it significantly extends the capabilities of radiodiagnostic methods to image cartilaginous and soft tissues and also facilitates with greater accuracy the assessment of the condition of the entire joint [48].

Researchers' opinions differ regarding the value of the arthrographic examination of children with congenital hip dislocation. For example, arthrographic examination significantly extends an anatomical picture of the hip joints because it provides information on the state of cartilaginous and soft tissue elements. In the absence of the ossification center of the epiphysis, arthrographic imaging allows the assessment of the degree of enchondral ossification of the femoral head and its shape, size of the ossified portion of the acetabular roof as well as the severity of intra-articular grafts [53]. However, subsequent studies emphasize that arthrography does not provide sufficient information about changes in the soft tissue and cartilaginous structures of the joint [54], and the significance of this method is only historical.

In summary, modern radiodiagnostic methods greatly facilitate establishing a diagnosis and planning further treatment. In our opinion, diagnostic techniques with minimal exposure to radiation are promising due to their high ability to penetrate tissues and the ability to administer them multiple times to the same patient.

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