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REVIEW

Developmental dysplasia of the hip: ultrasound evaluation

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Abstract
Developmental dysplasia of the hip (DDH) is a commonly encountered pathology in everyday pediatric radiology practice. Early detection of the condition and early institution of therapy are crucial in optimizing patient outcomes and preventing long-term morbidity. Ultrasound is the imaging modality of choice in evaluating DDH in patients less than 4 months of age and is also used to evaluate infants undergoing treatment with an abduction device to monitor therapy response. This article will begin with a general review of DDH, including the underlying pathophysiology of the condition and which patients meet screening criteria for developmental hip dysplasia ultrasound assessment. The paper will then describe the ultrasound techniques utilized in screening for DDH and how to apply the Graf classification system to determine if a hip is normal or dysplastic, as well as how to grade the severity of dysplasia. Finally, the paper will address specialized ultrasound techniques used to follow patients undergoing treatment with an abduction device to monitor therapy response.

Keywords Hip · Dysplasia · Subluxation · Dislocation · Infant · Ultrasound

Introduction

Developmental dysplasia of the hip (DDH) comprises a spectrum of anatomic abnormalities of the hip joint ranging from varying degrees of dysplasia to subluxation and dislocation [1]. The condition was previously referred to as congenital dysplasia of the hip (CDH). This terminology, however, was considered problematic and was replaced by the term DDH, which more accurately reflects the true course of the condition, which can occur either prenatally or postnatally in the first few months of life [2]. DDH is the most common hip pathology in infants, with an estimated incidence between 1.5–20 per 1,000 neonates, or approximately 1% of newborns [1–4].

Early detection and institution of therapy for DDH is incredibly important to prevent long-term complications of the condition, including the development of osteoarthritis, pain, gait abnormalities, and leg length discrepancies [2, 5]. It is approximated that up to one third of total hip arthroplasties performed in patients under the age of 60 years may be secondary to complications of DDH [3]. Ultrasound (US) is the imaging modality of choice for detection of DDH in infants less than 4 months of age and is also helpful for monitoring response to therapy [2, 3]. Initial treatment of hip dysplasia is often conservative with the use of an abduction device such as a Pavlik harness, though severely dysplastic hips or those which do not respond to conservative management may require closed reduction or even possibly open reduction and pelvic osteotomies [4]. The purpose of this paper is to review the pathophysiology of DDH, describe the screening criteria and US techniques to evaluate for DDH, discuss the ultrasound classification systems, including the Graf system, for diagnosis and management of DDH, and to highlight the role of US to monitor therapy response in select patients.

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Pathophysiology of DDH

Although the exact pathophysiology of DDH is not entirely known, it is thought to be multifactorial, related to a combination of mechanical, hormonal, and genetic factors [3]. Normal development of the hip joint relies on a balanced relationship between the acetabulum and the femoral head. If this is not present, the resulting hip may demonstrate abnormal morphology with a shallow acetabulum and poor femoral head growth [1].

DDH typically develops in the last 4 weeks of gestation or in the immediate postnatal period and is attributed to three main factors: ligamentous laxity, limited hip mobility, and acetabular dysplasia [2, 3]. In certain susceptible infants, abnormally increased laxity of the hip capsule and surrounding ligamentous structures has been ascribed to the maternal hormone relaxin and a higher number of estrogen receptors [3]. Excess motion at the hip joint related to ligamentous laxity disrupts the normal interactions of the joint and can lead to acetabular dysplasia and poor hip development. Limited fetal and neonatal hip mobility, such as with prolonged in utero breech positioning, is also associated with impaired hip development due to contracture and shortening of the iliopsoas muscle which can lead to femoral head subluxation or dislocation [3]. Acetabular dysplasia can also result in abnormal stretching of the capsular ligaments and movement of the femoral head. Initially, the labrum may be everted and flattened by the dislocated femoral head and the hip capsule may be further restricted. Fibrofatty pulvinar tissue and the iliopsoas tendon may prevent reduction of the femoral head, and in some patients, the labrum can invert and further block reduction of the hip [2].

Risk factors for DDH

There are four main risk factors associated with DDH (Table 1):

1) Female gender, with relative risk (RR) of 2.5 [6] and an odds ratio (OR) of 3.8 [7]. This is postulated to relate to increased sensitivity to the influence of maternal hormones associated with relaxing the ligamentous structures surrounding the hip [2].
2) Breech presentation, with a RR of 3.8 [6] and OR of 5.7 [7].
3) Positive family history (specifically in a parent or sibling), with RR of 1.4 [6] and OR of 3.8 [7].
4) Clicking hips at clinical examination with an odds ratio of 8.6 [7].

Table 1 Clinical risk factors for DDH [6, 7]

Clinical risk factor	Relative risk	Odds ratio
Female	**2.5**	**3.8**
Breech presentation	**3.8**	**5.7**
Positive family history (parent/sibling)	**1.4**	**3.8**
Clicking hips on clinical examination	**N/A**	**8.6**

Other reported, although less correlated, risk factors include ethnicity, oligohydramnios, associated congenital lower limb or musculoskeletal deformities, and tight lower limb swaddling [6–11]. Additionally, DDH has been found to occur approximately three times more frequently on the left compared to the right, likely related to fetal positioning of the left hip against the maternal spine, which may restrict movement of the hip [2, 3, 6].

US screening for DDH

A hip exam should be a regular component of neonatal and infant well-child screening visits. Examples of clinical exam findings which may prompt further work-up for DDH include asymmetric skin folds, leg length discrepancy, limited hip abduction, and hip instability [12, 13]. The Ortolani test and Barlow maneuver are specialized physical exams to evaluate hip instability. For the Ortolani reduction test, the hip is flexed at 90° and gently abducted. If the hip is dislocated and the femoral head is reduced with this maneuver, an audible "clunk" can be felt and heard [2, 12, 13]. For the Barlow dislocation test, the examiner will adduct and place gentle pressure on the hip by pushing the knee posteriorly and superiorly, feeling for dislocation of the femoral head in an unstable hip [2, 12, 13]. Although clinical examination can detect hip instability, it is not a reliable tool for diagnosing acetabular dysplasia. Despite reports of high specificity—up to 90%—its sensitivity may be as low as 50% [12, 14].

US imaging as a potential screening tool for DDH was first recognized by Graf in 1980 [15]. US allows for good visualization of the cartilaginous structures of the newborn's hip and allows for the performance of dynamic maneuvers to assess hip instability, a technique originally described by Harcke et al. [16]. Additionally, US is a non-ionizing and non-invasive imaging modality which does not require sedation or special preparation, making it an ideal screening tool for infants.

As a screening tool for DDH, US allows for early detection of DDH in newborn patients, who would benefit from prompt and typically noninvasive management, and excluding those without the condition. The newborn ultrasound screening policies for DDH, however, vary significantly across the globe, and can generally be divided into two main settings:

- Universal screening: In this setting, ultrasound of the hips is performed in all newborn infants, irrespective of risk factors or abnormal physical examination findings. The underlying principle of universal screening is to maximize early DDH diagnosis, ensuring no cases are missed. Countries which are known for this type of screening include Austria, Germany, Poland, Czech Republic, Slovenia, and Mongolia [9, 17, 18].
- Selective screening: In this setting, ultrasound of the hips is only performed in newborn infants that are at higher risk for DDH. The definition of which patients are considered at higher risk is also variable throughout the many selective screening policies. Countries which are known for this type of screening include the USA, Canada, Netherlands, Denmark, Sweden, France, Japan, and South Korea [9, 17, 18].

Comparing universal and selective ultrasound screening for DDH is a controversial topic, usually revolving around effectiveness, cost-effectiveness, and overall short- and long-term implications of a missed diagnosis and overtreatment [8] as exemplified in Table 2.

Another frequently debated topic is the ideal timing for US screening. In infants younger than 3 months, hips identified as mildly abnormal on US screening may spontaneously normalize as a part of the normal neonatal development, which happens in up to 90% of these cases by the age of 3 months [26]. In Europe, the time for first screening US varies from the first day of life to 4th-6th week of life [9]; in the USA, it is recommended after 3–4 weeks of life for patients with risk factors [11] and in Canada, between the age of 4 and 6 weeks, also for patients with risk factors [29].

Imaging of DDH US techniques

US is the modality of choice for imaging the neonatal hip, due to the predominantly cartilaginous anatomy of the joint at this age. As the child grows, increases in the soft tissue and muscle bulk make the hip deeper in relation to the skin surface, progressively reducing US image quality. Additionally, the development of the femoral head's secondary ossification center further reduces US reliability due to acoustic shadowing, while simultaneously enhancing the diagnostic utility of radiographs through increased conspicuity of the ossified structures [3].

There is no consensus regarding the exact age imaging should transition from US to radiography, especially given that ossification of the femoral head itself can vary widely among normal patients [30, 31]. However, ultrasound is generally not recommended after 4–6 months of age, at which point radiographs are usually more reliable [32].

Notably, in patients with established DDH, femoral head ossification may be delayed, in which case follow-up with US may be considered even after the 4–6 months of age [1, 3].

In general, newborn hip ultrasound is performed with high-frequency linear transducers (10–15 MHz), however in older infants and those with significant soft tissue and muscle bulk, moderate-frequency linear transducers (5–10 MHz) may be considered to improve penetration and overall image quality at the cost of image resolution. A template report example is available as supplemental material (SM1).

Graf method

Technique

The Graf method is the most used US screening method for DDH [reference]. It is primarily a static ultrasound technique in which the assessment is based on a single coronal image for each hip. This "standard plane" is acquired from a lateral approach with the transducer parallel to the bed, the patient in lateral decubitus and with the hips in a neutral position [15] (Fig. 1).

In this method, the hip classification is heavily dependent on precise angle measurements, more specifically the bony roof angle (alpha angle) and the cartilaginous roof angle (beta angle), which can provide a reliable and reproductible measurement when the proper technique is meticulously followed [reference]. This, however, also makes

Table 2 Universal screening versus selective screening

	Arguments in favor	Arguments against
Universal screening	Higher early detection rates [19] Reduced late presentations [20] Reduced long-term costs [21]	No significant differences in early or late outcomes compared to selective screening [19] Increased risk of overtreatment and related complications [19, 22, 23] Higher overall cost [21, 24]
Selective screening	Better cost-effectiveness [25] As effective as universal screening when combined with adequate physical examination [11, 26, 27]	Increased incidence of missed diagnoses/late presentation [28] Increased long-term costs [21, 25]

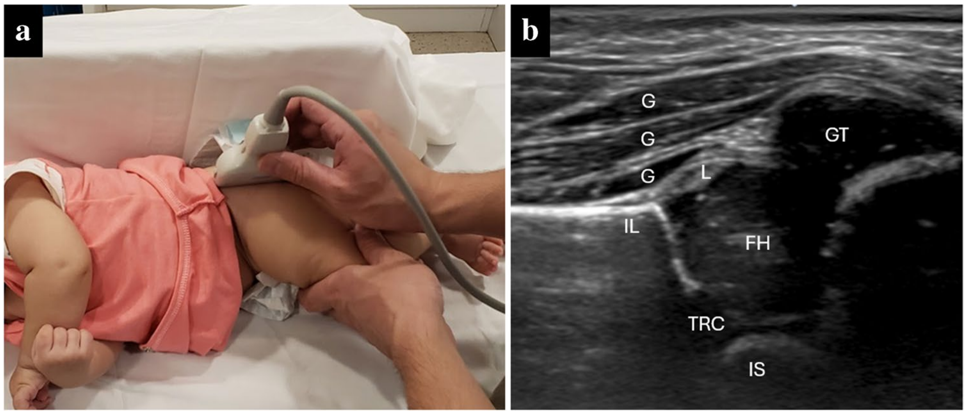


Fig. 1 Pictorial representation of how a coronal neutral image of the hip is acquired with the corresponding US images and anatomy. **a** Photograph demonstrating a sonographer acquiring a coronal neutral view in a volunteer patient. **b** Coronal US image of the hip in a normal volunteer with pertinent anatomy labeled. G, gluteal musculature; IL, ilium; AR, acetabular roof; TRC, triradiate cartilage; IS, ischium; L, labrum; FH, femoral head; GT, greater trochanter

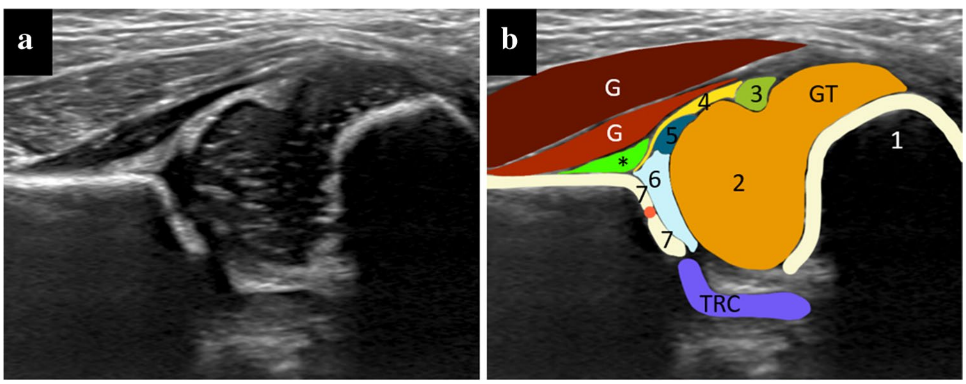


Fig. 2 **a** Standard coronal plane. **b** Standard coronal plane with annotations for the seven anatomical structures: 1 - femoral epiphyseal plate. 2 – Femoral head. 3 – Synovial fold. 4 – Articular capsule. 5 – Acetabular labrum. 6 – Cartilage acetabular roof. 7 – Osseous rim of the acetabulum (point where the acetabular convexity turns into a concavity – red dot). Other structures: TRC – triradiate cartilage. GT – greater trochanter. * - rectus femoris tendon. G – gluteus muscles

the Graf method highly operator-dependent and very sensitive to errors, in which even slight variations in probe positioning can significantly impact angle measurements, leading to potential misclassification [reference]. For this reason, proper training and continuous quality control are essential for maintaining reliability and accuracy in clinical practice [reference]. One suggested way of ensuring quality control is having radiologists perform reading

Table 3 Graf method anatomical structures of the "standard plane"

	Anatomical structures	Note/explanation
1	Chondro-osseous junction	Epiphyseal plate of the femur
2	Femoral head	
3	Synovial fold	To avoid mistaking with the labrum
4	Joint capsule	To avoid mistaking with the intermuscular septum
5	Acetabular labrum	
6	Acetabular roof sequence	Lateral: labrum Mid: cartilage acetabular roof Medial: bony socket
7	Osseous rim	Bony socket turns from concave to convex

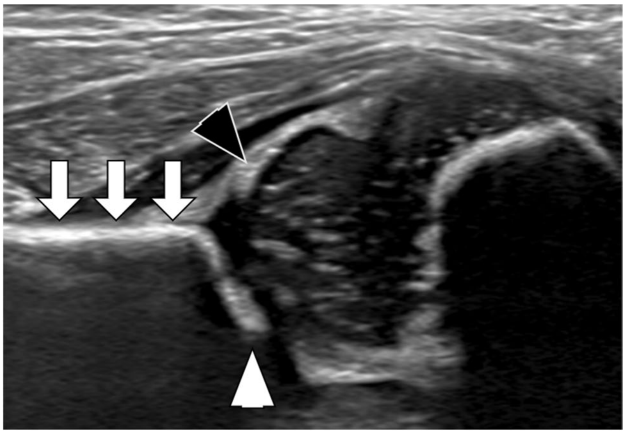


Fig. 3 Standard coronal plane in three landmarks: *White arrowhead*-first landmark: Lower limb of the iliac bone must be well defined. *Arrows*-second landmark: medial border of the iliac bone must be straight and parallel to the transducer. *Black arrowhead*: Third landmark, the labrum must be well defined

room checks for neonatal hip ultrasounds and have them available to aid in scanning if images are not appropriate.

Before the hip ultrasound is classified it must first be assessed for proper quality and position, which is performed by checking the visibility of seven anatomical structures (Fig. 2 and Table 3) and assessing three landmarks (Fig. 3 and Table 4) [33, 34].

Evaluation

Once the image has been deemed adequate, the hip morphology should be evaluated and the angles measured:

- Lines and angles (Fig. 4):
    - Baseline: a horizontal line through the lateral aspect of the iliac bone
    - Bony roof line: drawn from the bony acetabular rim to the triradiate cartilage, representing the inclination of the bony acetabular roof
    - Cartilage roof line: drawn from the bony acetabular rim through the middle of the labrum
    - Alpha angle: angle between the baseline and the bony roof line, reflecting the depth and steepness of the acetabular bony roof
    - Beta angle: angle between the baseline and the cartilage roof line, reflecting the position of the labrum relative to the acetabulum
- Superior bony rim (Fig. 5):
    - Sharp, slightly rounded, rounded or flat
- Cartilaginous roof morphology (Fig. 6):
    - Covering the femoral head, pressed upwards or pressed downwards

Classification

After the image has been properly evaluated, the hip is then classified into a specific type, according mostly to the resultant angles and patient's age, as seen on Table 4.

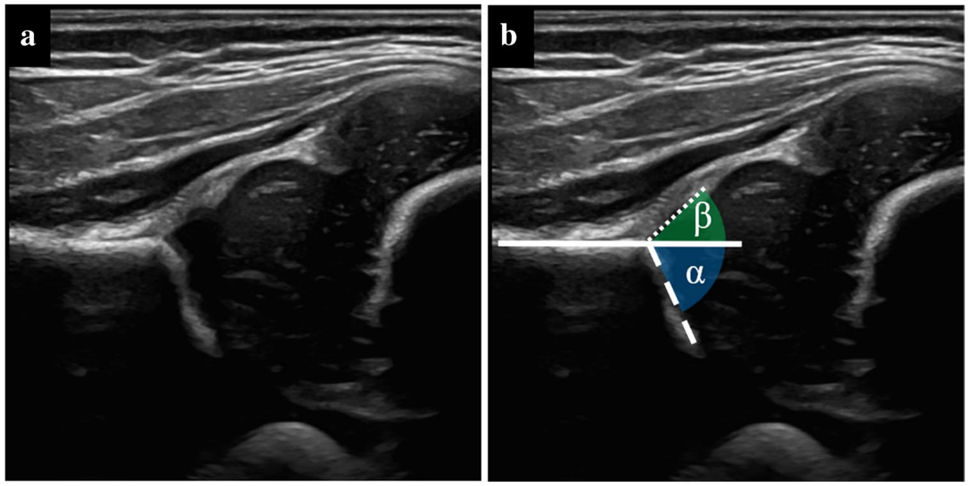
One of the most common pitfalls in the Graf method is improper patient/probe positioning, which will invariably lead to inaccurate angle measurements and misclassification of the hip, as exemplified in Fig. 7. Inaccurate angle measurement is usually reflected as an alpha angle measured as lower than it really is, meaning that improper technique usually leads to a false-positive scenario of a normal hip being classified as abnormal, rather than an abnormal hip being classified as normal, and such ideally the highest acquired alpha angle acquired should be considered [35]. The individual Graf classification categories will be described in the following paragraphs:

- The first category of the classification system is Graf type I, which represents a normal, physiologically mature hip [1, 9]. A Graf type I hip will have an α angle equal to or greater than 60°, with a morphologically normal acetabulum, which usually is related to a greater than or equal to 50% coverage of the femoral head (Fig. 8). Graf type I hips do not require imaging follow-up or treatment.
- The next categories within the classification scheme are Graf type IIa and Graf type IIb. For both these categories, the α angle will fall in the range of 50–59°. Graf type IIa morphology is reserved for patients less than 3 months of age and is generally considered a physiologically immature hip [1, 4] (Fig. 9). Although the vast majority of Graf type IIa hips will mature/normalize spontaneously by 12 weeks (approximately 95%), there is a small chance that these hips may become dysplastic [1]. For this reason,

Table 4 Graf method landmarks of the "standard plane"

	Landmark	Reasoning
1	Lower limb of the iliac bone	Plane crosses the center of the acetabulum
2	Straight appearance of the iliac bone	Plane crosses the middle of the acetabular roof
3	Acetabular labrum	Plane is parallel to the joint

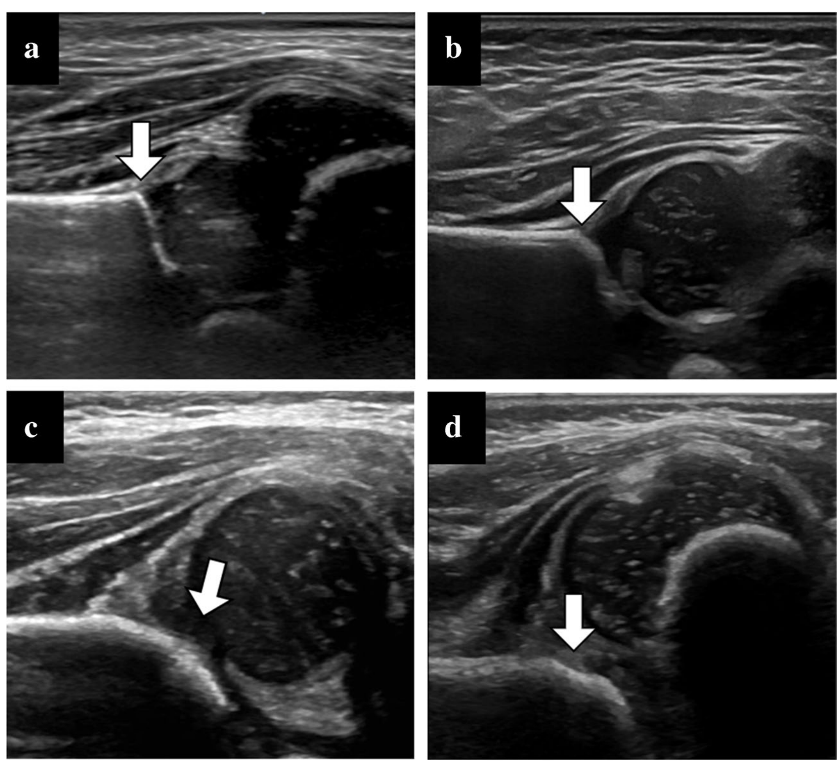
Fig. 4 **a** Normal hip ultrasound. **b** Overlay of lines and angles: full white line – baseline. Dashed line – bony roof line, drawn from the bony acetabular rim to the triradiate cartilage, forming the alpha angle with the baseline. Dotted line – cartilage roof line, drawn from the bony acetabular rim through the middle of the labrum, forming the beta angle



a follow-up US for Graf type IIa hips is recommended at around 3 months of age. Graf type IIb morphology is considered a dysplastic hip and is reserved for patients greater than 3 months of age at the time of initial US screening. Patients with Graf type IIb morphology should receive orthopedic surgery referral and may require treatment with an abduction device.

- The remaining groups of the Graf classification system describe dysplastic hips with varying degrees of severity. Patients who fall into these categories will require orthopedic referral and oftentimes treatment with an abduction device or surgical intervention. Graf type IIc and IId hips both have α angles ranging from 43–49° [1]. Graf type IIc hips have rounded or flattened acetabular rim morphology, though still maintain some coverage of the femoral head and can be stable or unstable (Fig. 10) whereas a Graf type IId hip is decentered or subluxed. Graf type III and IV hips have α angles measuring below 43°, with Graf type III considered a low hip dislocation and Graf type IV considered a high hip dislocation, with the labrum inverted and interposed between the femoral head and ilium [1] (Figs. 11 and 12).

Fig. 5 Classification of the superior bony rim. **a** Sharp. **b** Slightly rounded. **c** Rounded. **d** Flat



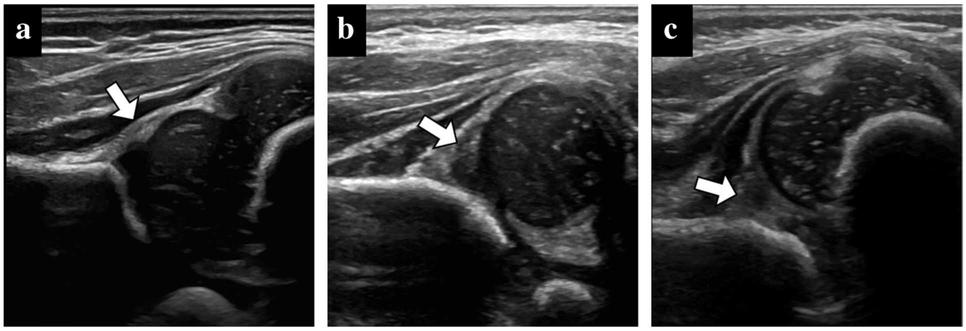


Fig. 6 Classification of roof morphology. **a** Covering femoral head–the labrum is visible (*white arrow*) and covers well the femoral head. **b** Pressing up–the labrum is visible (*white arrow*), but is displaced superiorly, still lying over the femoral head, which is poorly covered. **c** Pressing down–the labrum is not well defined; the entirety of the cartilaginous roof lies under the femoral head (*white arow*)

Harcke dynamic method

The Harcke method for dynamic evaluation of the hip is a technique that assesses both the joint morphology and joint stability [16]. The essential elements in this method are the coronal plane at rest and the transverse plane with stress, with the measurements of acetabular characteristics considered optional [16, 35].

Coronal plane

The coronal view may be performed with the hip in neutral position or flexion, with the patient either in lateral or dorsal decubitus, and regardless of the hip position, the image should be centered in the midacetabular plane to ensure consistency and is mainly used to evaluate acetabular development.

Measurement of the bony acetabular angle measurement (like Graf's alpha angle), which has already been discussed above, and femoral head coverage index, which will be discussed further, are optional.

The subjective analysis of hip morphology in the coronal plane follows the classification on Table 5.

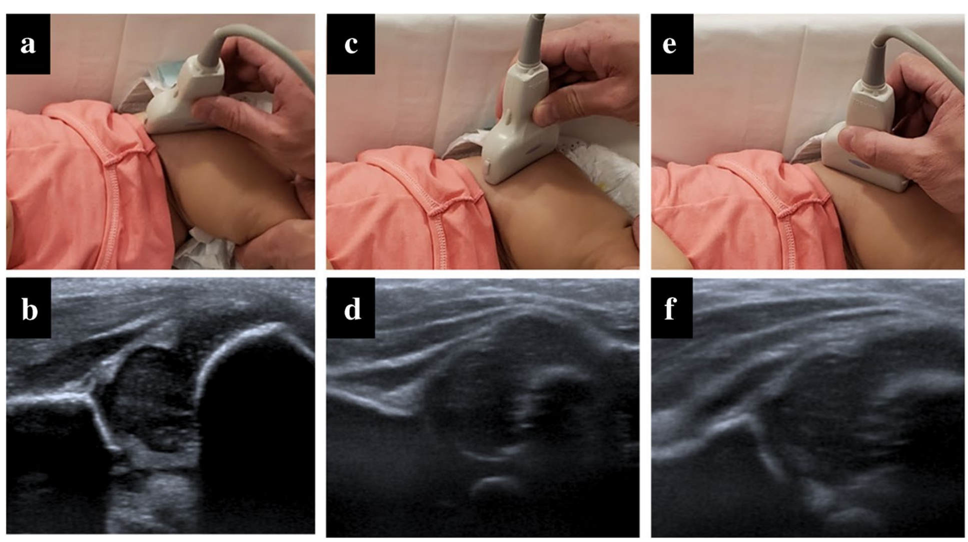
Transverse plane (dynamic stress view)

In the transverse plane, the patient is positioned either supine anterior oblique or in lateral decubitus. The transducer is oriented transversely to the body, or in an axial plane in relation to the pelvis, with the hip held in a 90° flexion.

The stress component involves a piston maneuver of the adducted hip, with the hip being pushed posteriorly, like the clinical Barlow test. Assessment of hip reduction can also be performed with a maneuver like the Ortolani test, with a pull and abduction of the hip joint.

In this view the femoral head is in the center of the image, with the ossified femoral metaphysis and ischium to each,

Fig. 7 Example of how improper probe positioning changes acetabular appearance and angles in the same patient. **a** and **b** Correct probe positioning. **c** and **d** Counterclockwise probe rotation of the probe. **e** and **f** Clockwise rotation of the probe



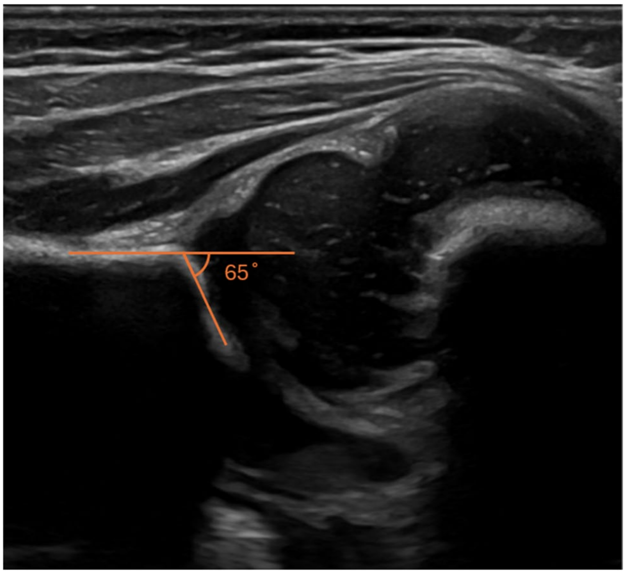


Fig. 8 A 5-week-old male with history of breech presentation. Normal hip screening ultrasound (Graf type I), demonstrating a sharp bony rim and an alpha angle greater than 60°

forming an echogenic "V" or "U" (Fig. 12). On the stable hip, there is no significant movement of the femoral head in relation to the ischium (supplemental video 1), while on the unstable hip it is possible to visualize the femoral head subluxation or even dislocation as it moves away from the ischium (Fig. 13 and supplemental video 2).

Stress maneuvers are not recommended in patients with established DDH diagnosis and who are being treated with the abduction devices, at least until the point where weaning from the harness commences [36].

The added value of the dynamic stress view to the static morphological assessment of the hip is also not very well established, with very few studies on the subject; however, there is some evidence that instability in morphological normal hips may have a correlation with late onset DDH [37] and also that instability may relate to patient outcomes [38]. It is important, however, to note that some degree of instability or laxity can be seen in normal newborns and will usually resolve spontaneously in the setting of a normal morphology hip [37].

Femoral head coverage percentage

This method was initially described by Morin et al. [39] with other similar variants being described subsequently [40–42], and revolves around the idea of measuring the percentage of the femoral head covered by the bony acetabulum. It is also based on a single image per hip, in the coronal plane like the coronal plane in Graf's and Harcke's method (Table 6). The hip may be flexed or neutral, and the patient may be positioned either on dorsal decubitus or lateral decubitus [39–41].

The acetabular coverage percentage is calculated by dividing the lateral length of the femoral head covered by the acetabulum by the lateral diameter of the femoral head (Figs. 14 and 15). As a general rule, a femoral head coverage greater than 50% is considered normal, as it correlates with an alpha angle of more than 60° [42].

Pubo-femoral distance

Initially described by Couture et al. [43], this method consists of measuring the distance between the medial margin of the femoral head and the lateral margin of the ossified pubic bone. Oblique coronal images (transducer obliqued posteriorly approximately 20°) are acquired with the patient in a supine position.

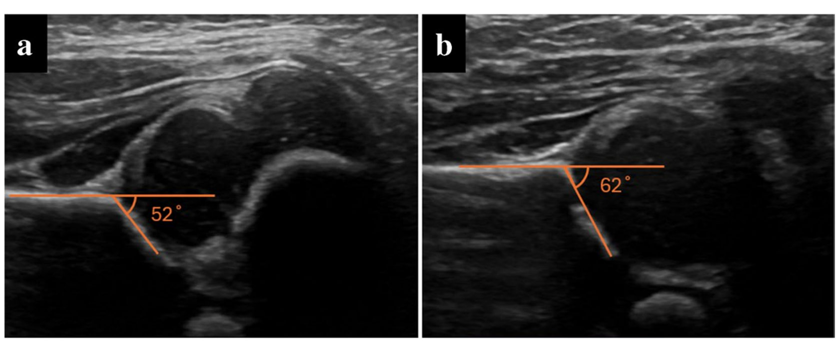


Fig. 9 Physiologic immaturity. **a** A 17-day-old boy with history of breech presentation and abnormal physical examination right hip ultrasound demonstrating a rounded bony rim, with an alpha angle of 52°, classified as Graf IIa. **b** Follow-up with patients at 3 months of age (no treatment) demonstrates progression of the hip, which now demonstrates a sharp bony rim and alpha angle of 62°, classified as Graf I and confirming the prior diagnosis of physiologic immaturity

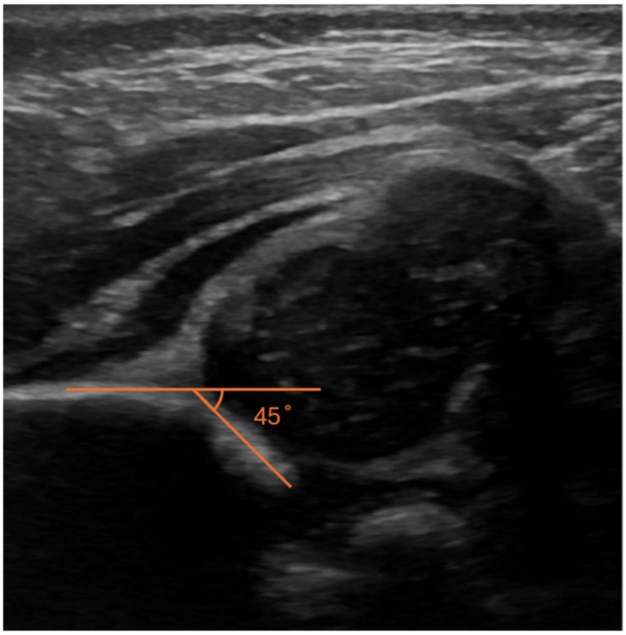


Fig. 10 Screening ultrasound in a 30-day-old female with positive family history (sibling) for DDH and breech presentation demonstrating a rounded bony rim, with an alpha angle of 45° and maintained partial femoral head coverage, compatible with Graf type IIc

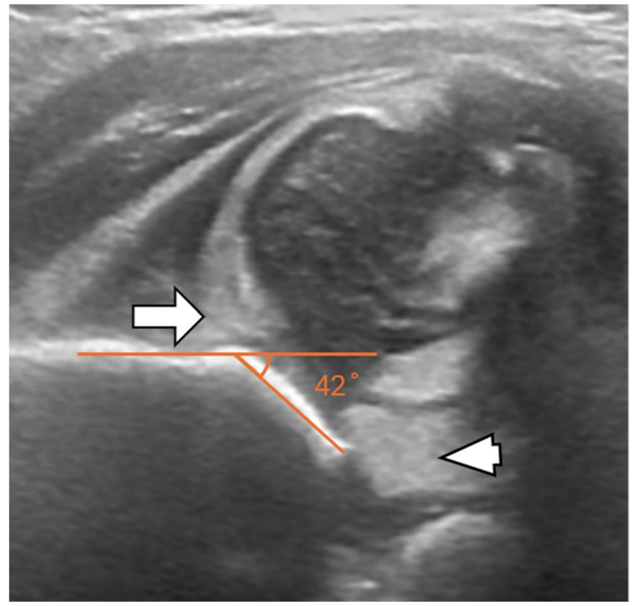


Fig. 12 US screening on a 6-week-old boy demonstrating a flattened bony rim, with an alpha angle of 41° and an ill-defined cartilage roof, which is mostly displaced under the femoral head (*arrow*), compatible with Graf type IV. Also note the preeminent fatty pulvinar within the acetabular fossa (*arrowhead*)

The ideal image requires that two cartilaginous structures be visible, namely the center of femoral head and the labrum, and three bone structures be visible, namely the horizontal iliac wing, bony acetabular roof at its greatest depth, and the pubic bone (Figs. 16 and 17) [44].

The pubo-femoral distance larger than 0.6 cm is considered abnormal, but in cases where the distance is less than 0.6 cm, an asymmetry of more than 0.15 cm is also considered abnormal.

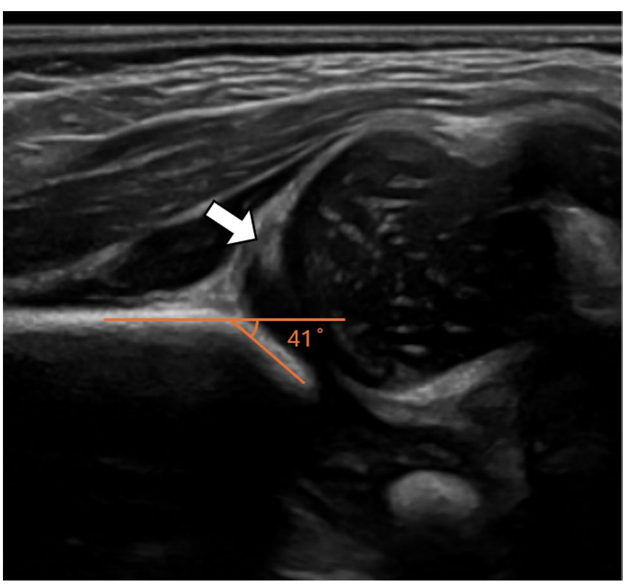


Fig. 11 US evaluation on a 2-day-old girl with hip clicking on physical examination demonstrating a flattened bony rim, with an alpha angle of 41° and a superiorly dislocated labrum (*arrow*), compatible with Graf type III

US imaging of treated patients

In addition to the standard views acquired for US exams performed to evaluate hip dysplasia, it is important for the radiologist to be familiar with specialized views for patients undergoing treatment for DDH in an abduction device such as a Pavlik harness. The abduction device maintains the hip in flexion and abduction and is used to treat infants with DDH where the hip is reducible [45, 46]. US imaging of the hips may be performed during treatment with an abduction device to either evaluate for proper positioning of the femoral head within the respective acetabula and/or to evaluate for improvement/resolution of DDH.

Imaging can be performed both in harness and out of harness in select patients, depending on the preference of the patient's orthopedic surgeon. Performing US while the patient is in harness can be challenging given the patient's hip is restricted to a flexed and abducted position. One alternative technique for evaluating proper femoral head position in these cases may be performed with the patient in a supine

Table 5 Sonographic classification based on the Graf method

Type	Maturity	*α* angle	Bony roof	Bony rim	Cartilage roof	Beta angle	Age	Suggested management
I	Mature	≥ 60	Good	Sharp/slightly rounded	Good coverage	Any	Any	No treatment or follow-up
IIa	Immature	50–59	Adequate	Blunt/rounded	Covered	Any	0–12 weeks	Ultrasound follow-up at 12 weeks
IIb	Dysplastic	50–59	Deficient	Rounded	Covered	Any	> 12 weeks	Orthopedics referral
IIc	Dysplastic (stable or unstable)	43–49	Severely deficient	Rounded or flat	Still covered	< 77	Any	Orthopedics referral
D (IId)	Decentering	43–49	Severely deficient	Rounded or flat	Displaced	> 77		Orthopedic referral
III	Eccentric-subluxed	< 43	Poor	Flat	Labrum pressed up	Any	Any	Orthopedic referral
IV	Eccentric-dislocated	< 43	Poor	Flat	Labrum pressed down	Any	Any	Orthopedics referral

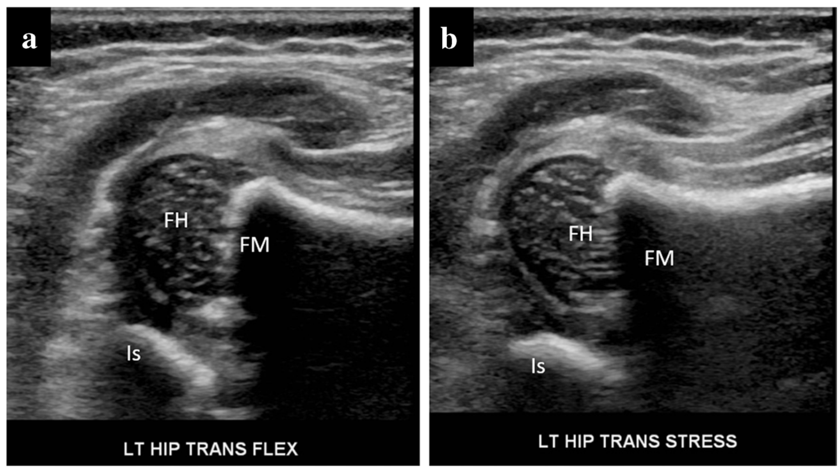


Fig. 13 Screening ultrasound in a 7-week female: **a** US evaluation in the transverse view with flexed leg. Is, ischium. FH, femoral head. FM, femoral metaphysis. **b** Stress view in the same transverse plane as **a** demonstrates posterior migration of the femoral head in relation to the ischium

position and the probe held in transverse orientation, over the anterior groin/hip [47, 48] (Fig. 18). A well-positioned femoral head will be aligned with both the acetabulum and pubic symphysis (Figs. 19 and 20). Modified coronal views can also be performed in harness to compare post treatment with pretreatment images, such as the alpha angle and femoral head coverage percentage [49].

The ideal timing for ultrasound (US) follow-up in patients undergoing treatment for DDH varies significantly, and there is no established consensus. Recommendations range from frequent short-interval follow-ups—weekly or at every clinic visit, particularly during the initial weeks of Pavlik harness application—to a more limited approach, performing

Table 6 Harcke method classification

	Acetabular morphology	Labrum	Femoral head position
Normal hip	Deep and concave contour with a sharply angled or minimally rounded margin	Narrow and triangular, covering the femoral head	Normally positioned in relation to the acetabulum
Borderline deficient hip	Straighten or shallow bony contour and rounded margin	Mildly widened labrum, still covering the femoral head	Normally positioned in relation to the acetabulum
Dysplastic hip	Shallow and flattened bony contour with distinction loss of the margin	Displaced cranially and deformed	Normally positioned in relation to the acetabulum or displaced by interposition of cartilaginous tissue

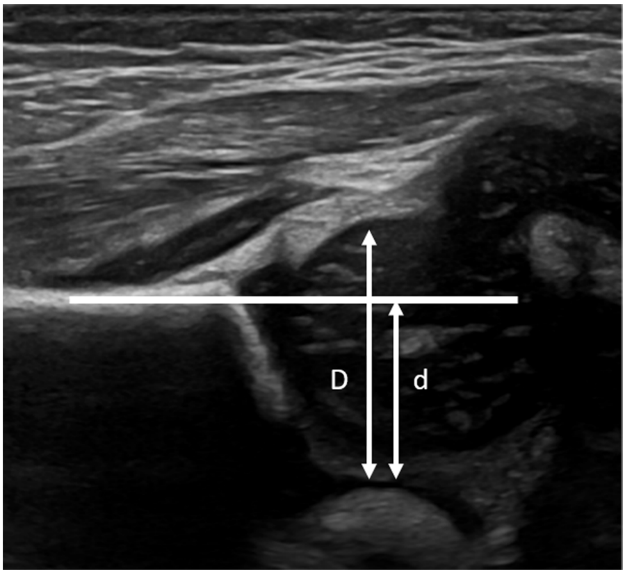


Fig. 14 A 4-month-old girl screening ultrasound demonstrates a well-covered femoral head, in which the ratio between length of the covered femoral head (d) and the total femoral head (D) is greater than 50%

ultrasound only within the first 4 weeks and again at treatment conclusion [50–52].

Avascular necrosis (AVN) of the femoral head is a rare but serious complication associated with DDH treatment, occurring with both nonsurgical and surgical interventions [53]. The role of US in detecting AVN is currently limited, with nonspecific sonographic findings such as patchy

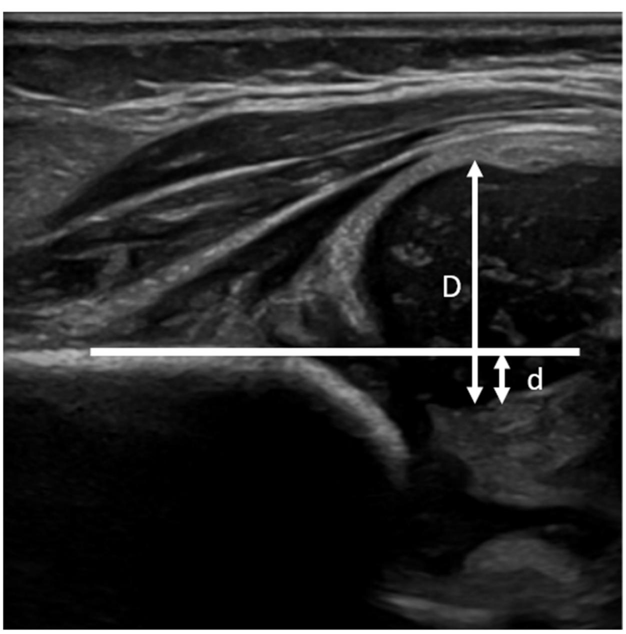


Fig. 15 A 2-month-old girl screening ultrasound which demonstrates under coverage of the femoral head, with a d/D ratio of less than 50%

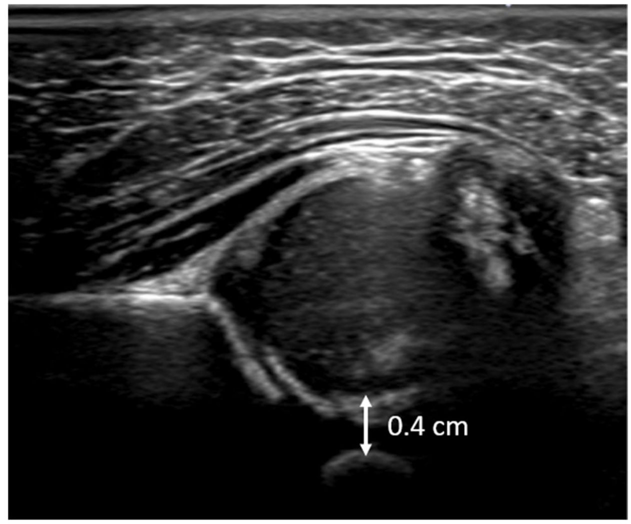


Fig. 16 Screening ultrasound in a 4-week-old boy, with a normal hip ultrasound demonstrating a 0.4-cm pubo-femoral distance

increased echogenicity reported in case studies [54]. Recent research, however, has explored the potential of contrast-enhanced ultrasound to assess femoral head perfusion, aiming to identify early predictors of AVN [55].

Conclusion

Developmental dysplasia of the hip is a commonly encountered pathology in infants. Patients have better outcomes and less late complications, such as osteoarthritis, when the

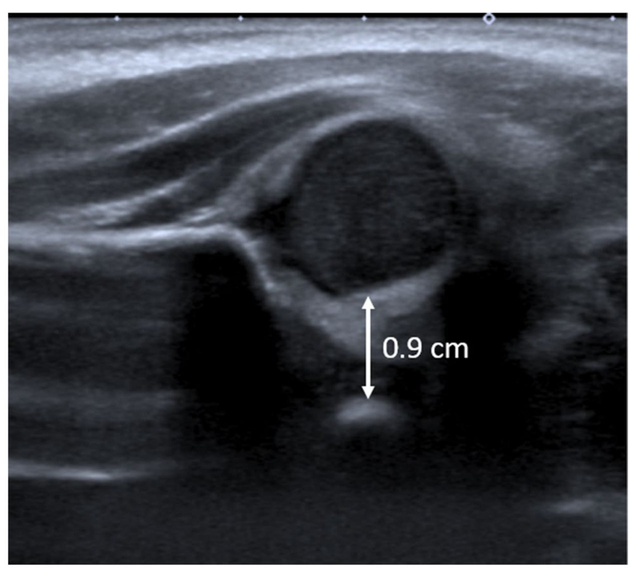


Fig. 17 Screening ultrasound in a 3-week-old girl, with an abnormal hip ultrasound, demonstrating a 0.9-cm pubo-femoral distance

Fig. 18 Transverse anterior scanning technique probe positioning for patients using harness

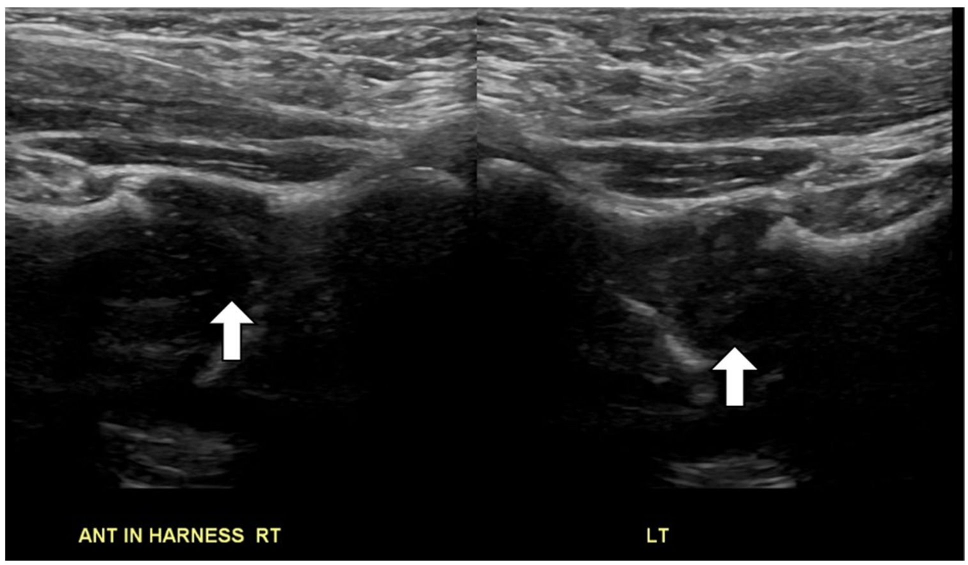


Fig. 19 Transverse anterior scanning technique with bilateral femoral heads well positioned within the respective acetabula (*arrows*)

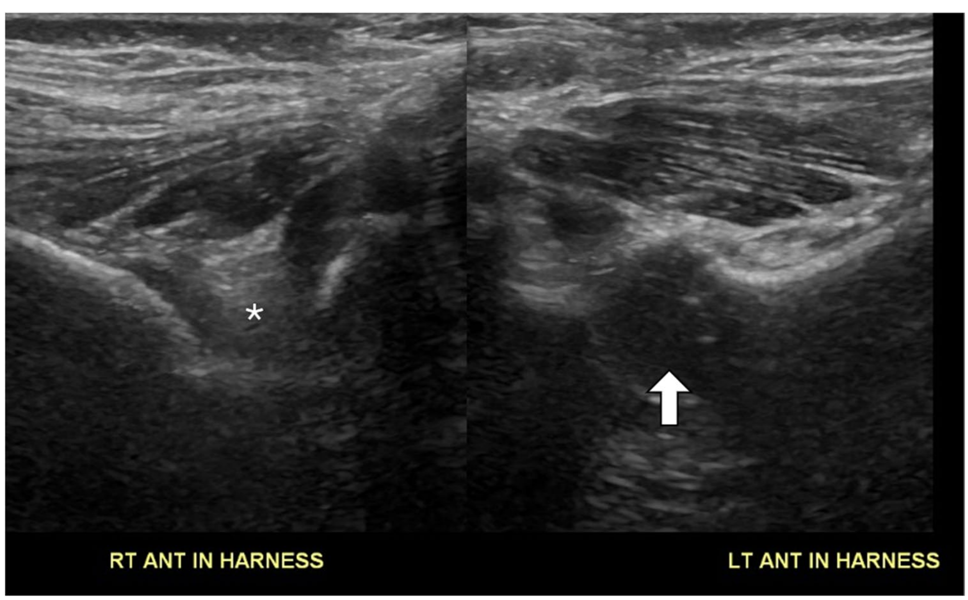


Fig. 20 An 8-week-old female treated for right DDH. Anterior US views of the hips acquired with the patient in harness, demonstrating right hip posterior dislocation, with femoral head not visualized within the acetabulum (*asterisk*) and normal left femoral head (*arrow*)

condition is detected early and effective nonsurgical options for treatment can be initiated. Dynamic hip ultrasound is an incredibly valuable and reliable diagnostic tool to evaluate for developmental hip dysplasia in infants. Ultrasound is also helpful to assess patients undergoing treatment in an abduction device to ensure that the hips are adequately aligned within the harness and to monitor treatment response.

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Author contribution Jillian Krauss and Marcelo Takahashi are co-first authors and contributed equally to the manuscript. Jonathan Samet is the senior author.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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