3D ultrasound to quantify lateral hip displacement in children with cerebral palsy: a validation study

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ABBRVIATIONS
LHC Lateral head coverage
MDD Minimal detectable difference
RMP Reimer’s migration percentage

AIM To assess the validity of a new index, lateral head coverage (LHC), for describing hip dysplasia in a population of children with cerebral palsy (CP).

METHOD LHC is derived from 3D ultrasound assessment. Twenty-two children (15 males, seven females; age 4–15y) with CP undergoing routine hip surveillance were recruited prospectively for the study. Each participant had both a planar radiograph acquired as part of their routine care and a 3D ultrasound assessment within 2 months. Reimer’s migration percentage (RMP) and LHC were measured by the same assessor, and the correlation between them calculated using Pearson’s correlation coefficient. The repeatability of LHC was investigated with three assessors, analysing each of 10 images three times. Inter- and intra-assessor variation was quantified using intraclass correlation coefficients.

RESULTS LHC was strongly correlated with RMP (Pearson’s correlation coefficient=−0.86, p<0.001). LHC had similar inter-assessor reliability to that reported for RMP (intraclass correlation coefficient=0.97 and intra-assessor intraclass correlation coefficient=0.98).

INTERPRETATION This is an initial validation of the use of 3D ultrasound in monitoring hip development in children with CP. LHC is comparable with RMP in estimating hip dysplasia with similar levels of reliability that are reported for RMP.

Hip dysplasia is a common developmental problem for children with cerebral palsy (CP) with a prevalence of around 35% to 40%.1,2 Hip dysplasia has the potential to cause severe pain and reduced function and, in extreme cases, can progress to complete dislocation.3,4 The risk factors for hip dysplasia and dislocation include age,5–8 subtype of CP,7,8 and motor function, with patients in Gross Motor Function Classification System (GMFCS) level V being at greatest risk.2,5,8 Progression to symptomatic hip dysplasia and dislocation can be prevented using a variety of surgical interventions.

To reduce the risk of significant hip dysplasia, surveillance programmes have been developed to monitor children with CP. These programmes rely on measurements made from planar radiographs of the hip to quantify hip displacement and acetabular development. Different indices have been developed, however Reimer’s migration percentage9 (RMP) is the most widely adopted. RMP is measured from a planar radiograph, which is a 2D projection of a 3D problem. As a result, RMP may be prone to systematic and random errors due to variation in patient positioning, and estimation of the RMP from planar images.10–12

3D imaging modalities, such as computed tomography (CT) or magnetic resonance imaging (MRI), have the potential to provide more reliable and complete assessment of hip development than planar radiographs. However, they are not without limitations. CT scans involve significant amounts of ionizing radiation, which is not acceptable in routine monitoring, MRI is expensive, and both modalities are susceptible to movement artefacts. To achieve optimal image quality using MRI or CT, a significant proportion of children would be likely to require sedation or anaesthesia. In contrast, 3D ultrasound is relatively quick and, given the non-ionizing nature, the images can be acquired safely multiple times if the patient moves during acquisition. Therefore, 3D ultrasound may provide a suitable alternative to planar radiographs for the routine surveillance of hip dysplasia.

The primary objective of this study was to perform preliminary validation of 3D ultrasound for the assessment of lateral displacement of the femoral head in children with CP. For this, a new ultrasound-based index, lateral head coverage (LHC), is defined and compared with RMP. The
secondary objective was to establish the intra- and inter-assessor reliability of our new index, LHC.

**METHOD**

**Participants**

Twenty-two participants (15 males, seven females), aged between 4 and 15 years, were recruited to the study. Participants were identified from paediatric orthopaedic clinics at a tertiary-level teaching hospital. The inclusion criteria stipulated that the participants must have a diagnosis of CP, be aged between 2 and 16 years, have had a 2D radiograph of the hips as part of their routine clinical management within the last 2 months, and not have undergone bony surgery to the acetabulum.

**3D ultrasound assessment**

Ultrasound images were acquired using either the Philips EPIQ 7 (Koninklijke Philips, Amsterdam, the Netherlands) with a 3D array probe, or the GE Voluson (GE Healthcare, Chicago, IL, USA) with a mechanical sweep probe. The depth of the scan was set between 6cm and 8cm, depending on the child’s size, with a sweep angle of 60°. Each child was positioned so that they were side-lying with hips extended as close to neutral as possible. The probe was orientated parallel to the superior–inferior axis of the pelvis over the lateral aspect of the hip. To optimize image acquisition, the greater trochanter was identified, and the probe was moved posterior–superiorly to obtain an optimal view of the femoral head and lateral acetabular border (Fig. 1). Images were saved and exported in DICOM or GE.vol (GE Healthcare) format.

Slicer v4.10.1, an open source image processing software (https://www.slicer.org/), was used for image analysis. The slice in the coronal plane with the maximum femoral head cross-section that also corresponded with the maximum femoral cross-section in the sagittal plane was selected for analysis (Fig. 1). A ‘best fit’ sphere was fitted to the femoral head and the diameter measured as an estimate of femoral head diameter. The lateral aspect of the acetabulum was also identified in the same medio-lateral image slice, and the lateral distance between the acetabulum border and the lateral aspect of the femoral head measured. The ratio of the two measurements was taken and deducted from 1 to give an estimate of the proportion of the femoral head that was covered by acetabulum. We will refer to this new index as LHC. LHC is an index for quantifying the femoral head coverage in the coronal plane, where ‘e’ is the distance in the lateral plane from the lateral aspect of the acetabulum to the lateral aspect of the femoral head, and ‘d’ is the diameter of the ‘best fit’ sphere.

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LHC = 1 - \left( \frac{e}{d} \right) \times 100
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Because of the construction of an ultrasound image it is not possible to create a mathematically equivalent index. For this reason, LHC measures coverage of the femoral head by the acetabulum, and not the proportion of the femoral head that is uncovered, as is done in RMP.

It was necessary to exclude some hips from the validation study if the necessary bony landmarks could not be identified in either the X-ray or the 3D ultrasound. Table 1 shows each participant and hip with details of inclusion/exclusion in this study. LHC was measured on the remaining 24 hips, which met the image inclusion criteria, by assessor 1.

Radiographs were acquired as part of the routine clinical care of each child under the standard positioning protocols used for hip surveillance. Participants were supine ensuring that the hips were as close to neutral in rotation, abduction/adduction, and flexion/extension as the children’s hip ranges allowed. The radiographers were unaware of the children’s participation in a research study. RMP was measured by assessor 1 and the classic method was used (i.e. using the lateral aspect of the acetabulum) (Fig. 1) because of its superior reliability. All measurements were made using the image analysis package PACS Sectra IDS 7 (v21.1.5 2096; Sectra AB, Linköping, Sweden). All RMP measurements were made with an interval of at least 1 week from the corresponding ultrasound measurement.

**Repeatability**

Eleven of the 24 hips included in the study were selected at random to investigate the repeatability of the 3D ultrasound image analysis. Three assessors with varying experience in analysing 2D B-mode ultrasound (2mo–7y) analysed the images. Assessor 1 had 6 months experience of analysing 3D ultrasound images of the hip, while the other two assessors had no prior experience in analysing these images. The two inexperienced assessors underwent an initial training session led by assessor 1 and had an opportunity to practice, compare, and receive feedback on a training set of images before beginning the study. All study images were different to the training images. Each assessor used Slicer v4.10.1 to analyse the images. All identifying information was removed. In the first session, each image was analysed twice with the image order randomized. In the second session, at least 1 week later, each image was analysed once, resulting in each image being analysed three times by the three assessors across the two sessions. All scores were sent to the study coordinator for compilation. One image was removed from the study as the acetabular border was consistently not visible in the slice chosen for analysis by the assessors.

**What this paper adds**

- Reliability of measuring 3D ultrasound assessment of lateral head coverage (LHC) was comparable with reported Reimer’s migration percentage (RMP).
- Strong correlation was found with 3D ultrasound assessment of LHC and the clinical standard (RMP).
Data analysis

To investigate whether the two indices were significantly different, a paired Student’s \( t \)-test was used. The RMP and LHC should be inversely proportional to each other, as one describes the proportion of the femoral head that is not covered by the acetabulum (RMP) and the other describes the proportion of the femoral head that is covered by the acetabulum (LHC). In order to conduct the paired Student’s \( t \)-test, \( 1 - \text{LHC} \) was calculated. Pearson’s rank correlation coefficient was used to assess the strength of correlation between the RMP and LHC. SPSS v26 (IBM Corp., Armonk, NY, USA) was used for the statistical analyses.

The inter- and intra-assessor repeatabilities of the LHC measurements were investigated using intraclass correlation coefficients (3,1) (two-way mixed, single measures). SPSS v26 was used to compute the inter-assessor intraclass correlation coefficient (3,1) (two-way mixed, single measures) using 90 measurements (3 assessors \( \times \) 10 images \( \times \) 3 repeats). The inter-assessor intraclass correlation coefficient was calculated using the first of the repeat images from each assessor (a total of 30 measurements, 10 per assessor).

To investigate potential bias between sessions, the mean of the two measurements from the first session for each assessor was deducted from the second session measurements. The means and standard errors of the mean (SEM) differences were calculated to allow calculation of the upper and lower bias limits.

To aid the establishment of the potential clinical utility of LHC, the minimal detectable difference (MDD) was calculated. The MDD is the smallest change in two measurements that can confidently (95% confidence intervals [CIs]) be taken as a true difference.

Ethical consent

Written consent was sought from the participants’ parents or legal guardians. The study was approved by the Health Research Authority and the national research ethics committee (Wales REC 7 study number 17/WA/0093).

RESULTS

Exclusions

Table 1 lists all recruits and details the rationale for exclusion from the validation study. Out of the 44 hips available, 24 were included in the study (age range 5y 7mo–13y 4mo, mean age 9y 5mo, standard deviation 2y 6mo). The most frequent reason for exclusion was that the ultrasound probe was not correctly orientated at the point of image acquisition. An amendment to the image acquisition protocol was made after participant 9, to ensure that the same view was reliably acquired and recorded. After this amendment, only two hips were excluded because of an ultrasound acquisition issue. Two further comparisons were excluded due to poor X-ray contrast rendering the border of the acetabulum.
In two instances, the child did not tolerate the ultrasound examination.

**Validation study**
RMP was not significantly different to 1–LHC (Student’s \( t \)-test \( \text{df} \ 23 \)=−0.494; \( p \)=0.626). Figure 2 shows the relationship between the RMP and LHC. There was a strong correlation between RMP and LHC, with a Pearson’s rank correlation coefficient of −0.86 (\( p < 0.001 \)).

**Reliability**
No bias between sessions was detected for any of the assessors. The SDs of the averaged measurements between the assessors ranged from 0.47% for image number 3, with best agreement, to 6.99% (Fig. 3). Intraclass reliability (intraclass correlation coefficient [3,1] (two-way mixed, single measures)) was 0.973 (95% CI 0.925–0.998), and a corresponding SEM of 3.6% and MDD 10%. Intraclass reliability was 0.982 (95% CI 0.967–0.991).

**DISCUSSION**
This paper describes the development of a new index, LHC, for the quantification of the lateral coverage of the femoral head by the acetabulum. LHC demonstrated a strong correlation with RMP, with 74% of the variation in LHC being explained by RMP. Further, both the inter-

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**Figure 2:** A comparison of Reimer’s migration percentage (RMP), measured by X-ray, with lateral head coverage (LHC) measurement measured by assessor 1 for 24 hips.

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**Figure 3:** Lateral head coverage (LHC) measured three times by three assessors for each of the 10 image volumes. Assessor 3 was the most reliable with a standard error of the mean (SEM) of 2.39%. Assessors 1 and 2 were very similar with SEMs of 2.91% and 2.97% respectively.

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**Table 1:** Inclusions/exclusions for each participant and each hip within the study

| Participant | Sex  | Left hip                                      | Right hip                                      |
|-------------|------|----------------------------------------------|-----------------------------------------------|
| 1           | Male | No orientation data recorded                 | No orientation data recorded                  |
| 2           | Male | No orientation data recorded                 | No orientation data recorded                  |
| 3           | Male | Included                                     | Included                                      |
| 4           | Female | No imaging with probe in correct orientation acquired | No imaging with probe in correct orientation acquired |
| 5           | Male | No acetabulum visualized                     | Included                                      |
| 6           | Male | Included                                     | No acetabulum visualized                      |
| 7           | Male | No imaging with probe in correct orientation acquired | No imaging with probe in correct orientation acquired |
| 8           | Female | No imaging with probe in correct orientation acquired | No imaging with probe in correct orientation acquired |
| 9           | Male | No imaging with probe in correct orientation acquired | Included                                      |
| 10          | Female | Included                                     | Included                                      |
| 11          | Male | Included                                     | Included                                      |
| 12          | Male | Included                                     | Included                                      |
| 13          | Male | X-ray not interpretable                      | X-ray not interpretable                       |
| 14          | Female | Included                                     | Included                                      |
| 15          | Female | Included                                     | Included                                      |
| 16          | Female | Child did not tolerate                       | Child did not tolerate                        |
| 17          | Female | Included                                     | Included                                      |
| 18          | Male | Included                                     | Acetabulum not visualized in slice chosen as maximal cross-section of femoral head |
| 19          | Male | Included                                     | Included                                      |
| 20          | Male | Included                                     | Included                                      |
| 21          | Male | Included                                     | Included                                      |
| 22          | Male | Included                                     | Acetabulum not visualized in slice chosen as maximal cross-section of femoral head |

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\( R^2=0.694 \)
and intra-assessor reliability of LHC were excellent, and similar to that reported for RMP. The SEMs and corresponding MDDs for LHC were also comparable with those reported for RMP (SEM range 2.98–3.9%, MDD = 8.3–11.5%). LHC is a measure that is simply constructed using both the sagittal and coronal planes of the ultrasound volume. Ensuring that the maximal cross-sectional area is found in two orthogonal slices removes a source of error to which 2D radiographs are prone. LHC gives an indication of the percentage of lateral coverage of the femoral head by the acetabulum, in contrast to RMP, which measures the percentage of femoral head that is uncovered. We considered using an index analogous to RMP but, to minimize confusion between our prospective index and RMP, we chose to create an index describing the coverage of the femoral head because LHC and RMP are informed by different bony landmarks, and are computed by different methods.

This is the first study to use 3D ultrasound to assess hip development in children with CP. There have been only a small number of studies that have used 2D ultrasound imaging in this population. Smigovec et al. visualized hips in children with severe CP (GMFCS level IV or V) using 2D B-mode ultrasound. The scanning technique described here is an adaptation of the method used by Smigovec et al. Smigovec and colleagues reported encouraging results, discriminating between measurements above and below a threshold RMP with greater than 90% sensitivity and specificity. Before their work, Tegnander and Terjesen investigated the feasibility and reliability of using 2D ultrasound to assess fully ossified hips in children above 2 years of age. Initially, they looked at ‘normal hips’ (i.e. children with no previous hip pathology) and concluded that the required bony landmarks could be visualized to measure the coverage of the femoral head by the acetabulum. They proposed normal limits for coverage (by their index) depending on age.

Previous efforts to investigate the use of ultrasound in visualizing hip development in older children and specifically children with CP may well have been stalled by limitations related to interoperator variance. In contrast, 3D ultrasound is proving to be an accurate and reliable tool in the morphological evaluation of the musculoskeletal system, specifically in soft tissue imaging, but few studies to date have analysed proximal femoral or hip geometry. Passmore et al. used freehand 3D ultrasound to measure femoral neck anteversion angle, comparing results to those obtained from MRI. The correlation was high (Pearson’s rank correlation coefficient = 0.94) with an average difference of 1.8° between the imaging modalities across the 10 individuals. 3D ultrasound was found to have repeatability coefficient of 3.7°, which was comparable with that of MRI, which was reported as 3.1°.

Limitations

There were a significant number of exclusions from this study, largely due to inexperience in the ultrasound image acquisition of the hip at the start of this study. Such early images, acquired with the probe not orientated in line with the superior–inferior axis of the pelvis, were excluded.

Hip dysplasia is a 3D maldevelopment of the hip and, as such, would ideally be monitored by 3D imaging. Traditional 3D imaging modalities (CT and MRI) are not valid options for routine monitoring of hip development in children with CP because of increased exposure to ionizing radiation (CT), the expense of the investigations, and the requirement for sedation or anaesthesia in younger children. When making clinical decisions, orthopaedic surgeons and others need to be aware of the limitations of measurements from planar radiographs in the assessment of the hip.

LHC was compared with RMP, as RMP is the clinical standard for routinely monitoring hip development in children with CP. This was a pragmatic decision for recruitment purposes. However, RMP is not a criterion standard measurement, and it is not clear what contribution errors in RMP measurement have on the comparison between LHC and RMP.

For more complete validation, LHC should be compared with a similar index derived from 3D imaging, where
error sources could be minimized and the comparative measurements could be considered a true criterion standard. Gose et al.24 compared a CT-derived index to RMP and reported a strong correlation (Pearson’s rank correlation coefficient=0.85, p<0.001) between the measurements, comparable with the agreement found in our study. Figure 4 shows a 3D render of the left hip from a child with CP. Using 3D ultrasound, detailed hip morphology can be visualized. However, to validate the observations, it would be of interest to compare 3D ultrasound to a criterion standard 3D imaging modality such as MRI or CT.

RMP and LHC rely on the identification of the lateral border of the acetabulum and a measurement of femoral head diameter/width. However, the two modalities construct images in different ways. Planar radiographs are projection images showing areas of high and low absorption of the X-rays as they pass through the object from source to receiver, which allows for high contrast between bone (highly absorbent) and surrounding soft tissues (less absorbent), normally resulting in clear 2D imaging of hip morphology. The width of the femoral head is measured at the level of Hilgenreiner’s line. Ultrasound images are constructed from the reflections of the soundwaves at borders between different tissues. Bony surfaces are highly reflective to these soundwaves and, as such, ultrasound cannot visualize structures that sit close to a bony surface. In order to get an estimate of femoral head size, a sphere of ‘best fit’ was fitted to the lateral curvature of the femoral head in both the sagittal and coronal planes (Fig. 1), and the diameter of the sphere was taken as an estimate of femoral head size. When comparing the estimates of femoral head diameter from ultrasound to those derived by X-rays we did not detect a systematic difference between the measurements. The absolute percentage error in the measurements was computed to be 10.1%. This error may be due to the errors associated with measurements made on both X-ray and ultrasound images.

Clinical implications
The use of ultrasound to evaluate hips in young infants has transformed the screening of developmental hip dysplasia.25 Developmental hip dysplasia is an umbrella term used to describe abnormal positioning of the femoral head and acetabulum in otherwise typically developing infants. Ultrasound lends itself well to imaging of the hip in the very young, as the hip has not ossified and therefore sound waves are able to partially penetrate through the hip joint, allowing visualization of the acetabulum. As the hip ossifies, it becomes impossible to get clear images of the joint. However, as this study has shown, it is still possible to visualize significant anatomical landmarks and make measurements of hip geometry that may have diagnostic value.

Using 3D ultrasound imaging would allow for more frequent and repeated assessments to be performed, because ultrasound is a non-ionizing imaging modality. Ultrasound imaging would also allow for the hip to be imaged in different positions, providing further information about hip development that cannot currently be collected from single radiographs. Repeated measurements in the same position would permit greater confidence in the estimation of hip displacement. Screening programmes often do not have frequent monitoring for children with CP who are less severely affected as they are less at risk of hip displacement. Depending on the programme, individuals may be discharged after a single ‘normal’ radiograph or receive a further X-ray at around the age of 8 years (after which very few hips go on to dislocate).6,8,26 Kentish et al.27 reviewed 1115 children who had been engaged in their hip screening programme. Of these, 28% had RMP of greater than 30%. In this group with high RMPs, 16% were in GMFCS levels I or II. Using a non-ionizing imaging modality such as 3D ultrasound would permit safe continued monitoring in the more able group.

CONCLUSION
This paper presents an initial validation of the use of 3D ultrasound in monitoring hip development in children with CP. The results show that LHC is comparable with RMP in estimating hip dysplasia, with similar levels of reliability to those reported for X-ray. With the potential to increase assessment frequency, the 3D ultrasound assessment technique could, as a minimum, provide a non-ionizing alternative for the monitoring of hip dysplasia in children with CP. It is also likely that the additional structures and views that can be imaged with ultrasound compared with a 2D radiograph could provide valuable information on hip management for individuals with CP. Further investigations are required to appreciate the full potential of 3D ultrasound in the monitoring of hip dysplasia in children with CP.

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