MRI-based assessment of acetabular version and coverage after previous Pemberton osteotomy in skeletally mature patients

Petri Bellova
Sophia Blum
Albrecht Hartmann
Falk Thielemann
Klaus-Peter Günther
Jens Goronzy

Abstract

Purpose In hip dysplasia the Pemberton osteotomy can modify the shape of the acetabulum and is indicated for children aged between two and 12 when the triradiate cartilage is still open. However, there have been concerns about acetabular retroversion following this type of osteotomy. The studies, however, have been based on plain radiographs. The aim of our investigation was to assess the 3D acetabular orientation in patients with previous Pemberton osteotomy after skeletal maturation.

Methods Ten patients with 12 operated hips were included who received Pemberton osteotomy for hip dysplasia between January 3, 2005 and March 25, 2011. Mean age at surgery and at follow-up were 7.2 years (sd 3.7) and 19.2 years (sd 3.7), respectively. MRIs were conducted with 1.5 T. Besides the measurement of acetabular version, the analysis included alpha angles, acetabular sector angles (ASAs) as well as modified ASAs (cartilage covered area angles). Furthermore, the presence of osteoarthritis (OA) as well as acetabular retroversion was determined on plain radiographs. Patient-related outcome measures included the international Hip Outcome Tool (iHOT) and EuroQol-5-Dimensions (EQ5D) scores.

Results In comparison with the contralateral native and healthy hips the operated hips showed similar version (19.5° (sd 4.6°) *versus* 18.6° (sd 7.0°); p = 0.974). Also, there were no differences in terms of femoral head sphericity (alpha angles) and acetabular coverage (ASA angles). Five of 12 Pemberton hips showed signs of beginning OA (Kellgren-Lawrence classifica-

tion I or II) while none of the non-operated hips did. Patients who received surgery before the age of six years had similar functional and radiological results when compared with patients who were older than six years at surgery. Among all patients, iHOT was 91.9 (sd 10.0) and EQ5D was 90.3 (sd 7.3)).

Conclusion The Pemberton osteotomy provides good long-term radiographic and functional results without compromising acetabular version or coverage.

Level of Evidence Level III: retrospective comparative study

Introduction

Developmental dysplasia of the hip (DDH) is the most common congenital deformity and frequently requiring surgical correction osteotomy in order to prevent early onset of secondary hip arthritis. Depending on the patient's age, surgical treatment options include different types of shelf and ilium osteotomies,[1-4] the Salter innominate osteotomy (SIO)[5] and reorientation osteotomies of the whole acetabulum.[6-10] A frequently performed treatment is the Pemberton osteotomy, which is indicated for children aged between two and 12 years when the triradiate cartilage is still open.[2]

The goal of the Pemberton osteotomy is to improve the anterolateral coverage of the hip joint. This is achieved by a dome-shaped pericapsular ilium-osteotomy. In doing this, a modification of the shape and radius rather than a re-orientation of the acetabulum is achieved. Being an incomplete osteotomy, the Pemberton osteotomy can be performed bilaterally during a single surgery as the pelvic continuity is not disrupted.[11]

Due to the reorientation of the acetabular roof in an anterolateral direction, there is an increased risk of increased anterocranial coverage mimicking acetabular retroversion. Retroversion itself might lead to femoroacetabular impingement (FAI) and subsequent early onset of

[1] Department of Orthopedics, Trauma and Plastic Surgery University Hospital Carl Gustav Carus, Dresden

Correspondence should be sent to Petri Bellova, University Center of Orthopedics, Trauma and Plastic Surgery, University Hospital Carl Gustav Carus, TU Dresden, Fetscherstr. 74, 01307 Dresden. Email: petri.bellova@uniklinikum-dresden.de

osteoarthritis (OA).[12] This problem has mostly been associated with the Salter osteotomy which also aims to improve anterolateral coverage.[13-16] Recently, a study by Wang et al[17] suggested that Pemberton hips also had signs of retroversion when compared with the non-affected, contralateral hips. In accordance with this, a study by Akiyama et al[18] found 37.5% of Pemberton hips to have signs of retroversion which was significantly more often when compared with patients that were treated with a brace only.

A major limitation of all these studies, however, is the lack of 3D imaging for the assessment of acetabular version. Plain radiographs may be highly biased by pelvic tilt and other inherent limitations of conventional radiographs.[19-22] MRI has the capacity of providing accurate measurements without radiation exposure.[23] To our knowledge, up to now no study has used MRI in the follow-up of DDH patients treated with Pemberton osteotomy.

The objective of this study was, therefore, to assess the 3D acetabular orientation by using MRI after skeletal maturation and to evaluate patients' function and health-related quality of life.

Patients and methods

Patient inclusion

A total of 47 consecutive patients who received Pemberton osteotomy due to DDH between January 3, 2005 and March 25, 2011 at our university were screened for inclusion in the study. Exclusion criteria for this retrospective study were: age younger than 14 years at follow-up examination; inability to undergo MRI; and neuromuscular disorders. In total, 32 patients had to be excluded and 15 patients remained for follow-up, of which five could not be investigated due to missing contact data (n = 2), refusal to participate (n = 2) or secondary total hip arthroplasty (n = 1). Finally, ten patients with a Pemberton osteotomy due to DDH were available for final follow-up (Fig. 1). These patients were invited to our clinic for a clinical and radiological follow-up visit including conventional radiographs as well as MRI. If pathologies were detected during this visit, further recommendations were issued. Approval was obtained by the local ethics committee.

One patient was operated on her right hip and seven patients on their left hip. Two patients received bilateral surgery. In two patients, an additional intertrochanteric varisation osteotomy was performed within the same surgery. Four patients were male and six were female. Further demographic data is displayed in Table 1.

Surgical technique

All osteotomies were performed by FT in a similar manner as originally described by Pemberton.[2]

The skin incision was made below the iliac crest extending from the anterior superior iliac spine one-third of the way towards the posterior superior iliac spine. The abdominal muscle attachment was identified and detached laterally from the iliac epiphysis. The iliac epiphysis itself with the attached muscles was separated into two parts, which were stripped subperiosteally from the anterior third of the ilium exposing the bone laterally and posteriorly down to the hip capsule as well as inside the pelvis until the sciatic notch was reached. The osteotomy was done with a narrow and curved osteotome through both cortices of the ilium separately. Starting just above the anterior inferior iliac spine (AIIS) the osteotomy of the outer cortices of the ilium extended posteriorly in a curved line above the attachment of the joint capsule down to the ilio-ischial limb of the triradiate cartilage. The image intensifier was used in order to avoid damage of the triradiate cartilage. The osteotomy of the inner cortices of the ilium, starting at the same point above the AIIS, was initially directed to the sciatic notch but extended in a curved manner to the ilio-pubic limb of the triradiate cartilage and backwards in order to complete the osteotomy of the ilium.

Since the triradiate cartilage is a flexible structure it can be used as a variable hinge. After completion of the osteotomy, the ilio-pubic and ilio-ischial limbs of the triradiate cartilage could be used to wrap the iliac portion around the head in an anterolateral direction. Using the image intensifier for control we were able to modify the size and shape of the acetabular correction individually. A bone graft was harvested from the iliac crest and positioned between both sides of the ilium osteotomy to secure the correction.
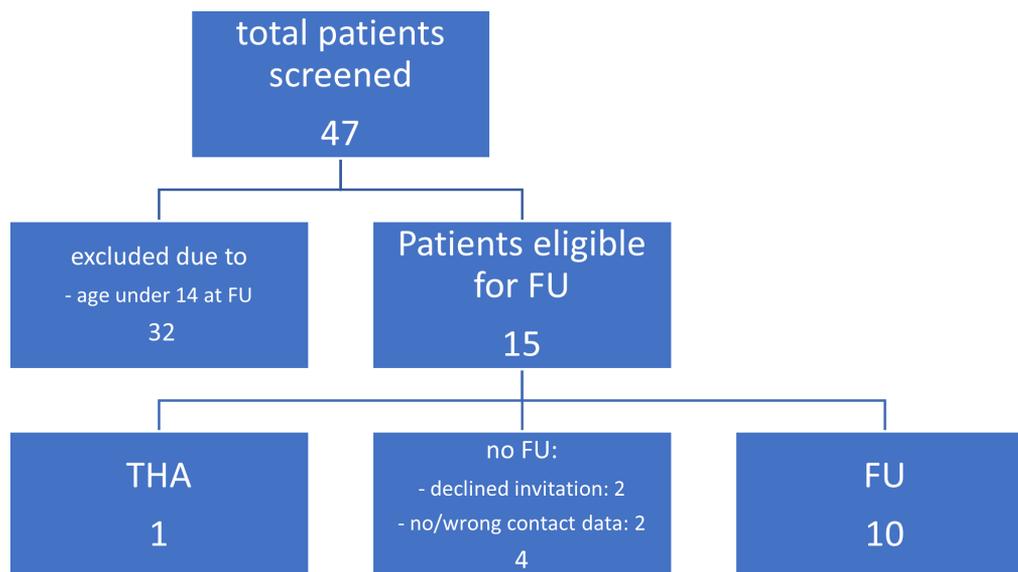
Clinical examination

Clinical examination at follow-up included assessment of the anterior and posterior impingement sign as well as the assessment of range of movement (ROM) for both hips. The ROM investigation included flexion/extension, abduction/adduction as well as the external rotation/ internal rotation in 0° and 90° hip flexion. The international Hip Outcome Tool (iHOT)[24] was chosen as a patient-related outcome measure (PROM) especially developed for joint preserving surgery. Furthermore, the EuroQol-5-Dimensions (EQ-5D)[25] score was obtained as a measure for health-related quality of life.

Radiographic examination

Conventional radiographic evaluation at follow-up consisted of a standard anteroposterior (AP) pelvic radiographs in supine position as well as a frog-leg lateral hip radiographs on the operated side.

On AP radiographs, lateral centre edge (LCE) angles[26] and acetabular indices (AI)[27] were measured for both the

```
                    total patients
                       screened
                          47

    excluded due to          Patients eligible
    - age under 14 at FU         for FU
           32                       15

        THA            no FU:              FU
         1          - declined invitation: 2      10
                    - no/wrong contact data: 2
                             4
```

Fig. 1 Strengthening the Reporting of Observational Studies in Epidemiology diagram of patient inclusion (FU, follow-up; THA, total hip arthroplasty).

operated as well as the non-operated hip whereas on frog-leg lateral radiographs, alpha angles were measured on the operated side. Furthermore, the crossover sign as well as the ischial spine sign were determined as indicators of acetabular retroversion.[20]

For grading of OA, the Kellgren and Lawrence (KL) classification[28] was assessed for both the operated and non-operated hips.

The MRI investigation at follow-up was conducted solely for study purposes. Non-contrast-MRI was performed with a 1.5-T Siemens AVANTO (Siemens AG, Munich, Germany) with a 3D isotropic fat saturated VIBE sequence and a slice thickness of 0.8 mm (field of view 295*450; TE 7.17 ms; TR 15.9 ms; and acquisition time 8 mins 13 secs). The pelvic scan was followed by a Half-Fourier Acquisition Single-shot Turbo spin Echo (HASTE) sequence covering the femoral condyle (field of view 400*400; TE 99 ms; TR 1000 ms; and acquisition time 0.57 secs). The patients' legs were positioned in a special fixation device to prevent possible leg movement during both sequences. All angles mentioned below were measured in multiplanar reformations created within the hospital picture archiving and communication system (IMPAX EE, AGFA, R20 XVI; Agfa HealthCare GmbH, Bonn, Germany). In order to standardize pelvic alignment, the centres of the reformation axis were aligned with the centres of the femoral heads both in the transverse and coronal planes, beginning with the right side followed by the left side.[23]

Modified acetabular sector angles (ASA) were measured in a clockwise manner from 9 o'clock to 3 o'clock (9/10/11/12/1/2/3 o'clock). The 3 o'clock position equals the traditional anterior acetabular angle while 9 o'clock

Table 1 Demographic characteristics and patient-reported outcomes of all operated patients

Demographic	Mean
Mean age at surgery, yrs (sd; range)	7.24 (3.71; 1.3 to 11.5)
Mean age at FU, yrs (sd; range)	19.16 (3.65; 14.5 to 23.6)
Mean FU, yrs (sd; range)	11.92 (1.71; 8.5 to 14.1)
Male, n (%)	5/12 (*41.7*)
Operated side right, n/N (%)	3/12 (*25*)
IVO, n/N (%)	2/12 (*16.7*)
Mean weight, kg (sd; range)	65.17 (13.04; 49 to 89)
Mean height, cm (sd; range)	170.75 (9.97; 152 to 184)
Mean BMI, kg/m² (sd; range)	22.46 (4.81; 16.76 to 31.53)
iHOT, % (sd; range)	91.85 (9.99; 70 to 99.6)
EQ5D, % (sd; range)	90.25 (7.31; 70 to 100)

FU, follow-up; IVO, intertrochanteric varisation osteotomy; BMI, body mass index; iHOT, International Hip Outcome Tool; EQ5D, EuroQol-5-Dimensions (score)

equals the traditional posterior acetabular angle. Furthermore, the cartilage covered area (CCA angle) between the acetabular edge and the acetabular fossa as well as the alpha angles were measured accordingly. The acetabular version was measured in the transverse plane passing through the center of the femoral head.[29] Furthermore, cranial acetabular version was measured in the transverse plane just below the roof level (1 mm to 2 mm). Femoral torsion was evaluated in an oblique view with a femoral neck bisecting axis at the proximal femur and a tangential axis touching the posterior femur condyles in a transverse plane at the distal femur (Fig. 2).[30]

Statistical analysis

Statistical analysis was performed using the SPSS software (IBM, V. 27, Chicago, Illinois).
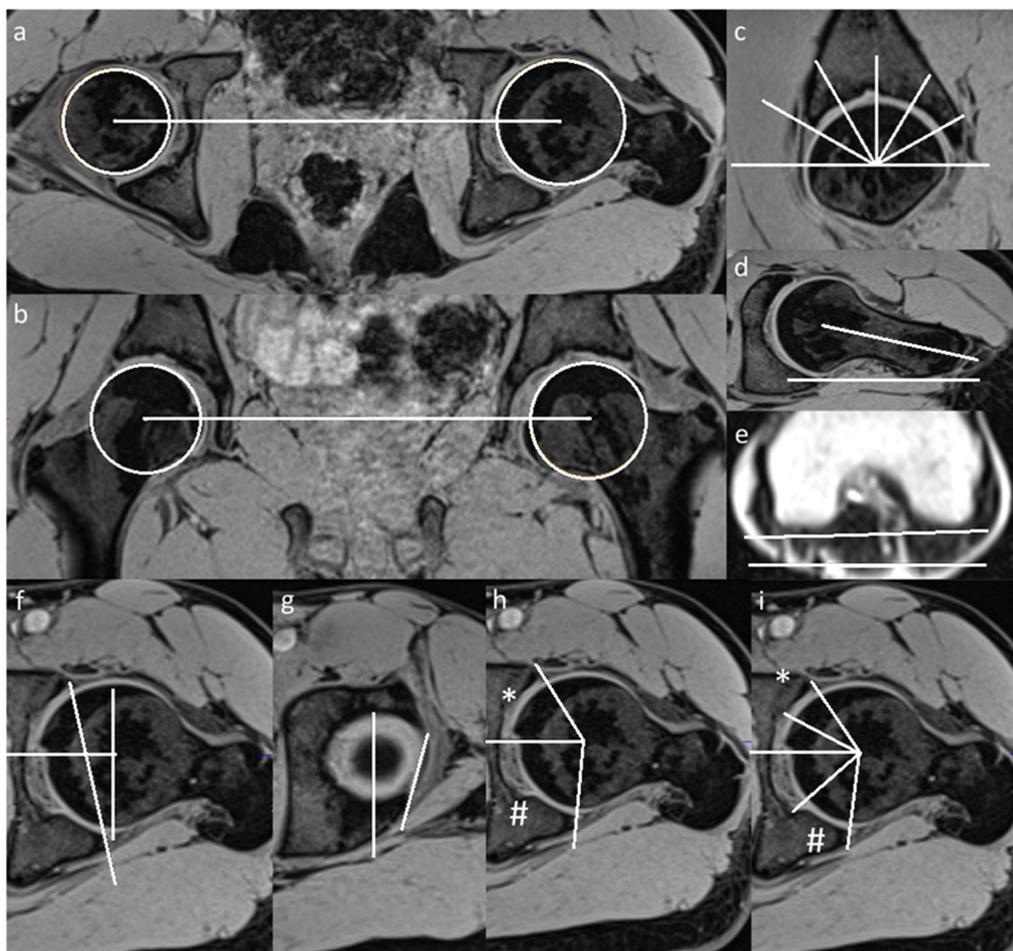
Fig. 2 MRI pelvic alignment and performed measurements: a-c) MRI alignment in the axial, coronal and sagittal plane presenting the measured clock wise plains; d-e) measurement of the femoral version; f) measurement of the anteversion at the femoral head center; g) measurement of the anteversion at the acetabulum roof; h) measurement of the anterior (*, 3 o'clock) and posterior (#, 9 o'clock) acetabular sector angle; i) measurement of the cartilage covered area anteriorly (*, 3 o'clock) and posteriorly (#, 9 o'clock).

Comparisons were drawn between the operated hips and the contralateral, non-operated hips as the control group. In total, 12 index hips and eight control hips were considered for the analysis. Continuous variables were presented as the mean (SD), and categorical variable were presented as counts and percentages. Between-group comparisons of continuous variables were performed using the Mann-Whitney U test. For comparisons of categorical variables, Fisher's exact test or the student's t-test was used. The significance level was set at $p < 0.05$.

Results

Patient's mean age at surgery was 7.2 years (1.3 to 11.5) and the mean age at follow-up was 19.2 years (14.5 to 23.6). The mean follow-up was 11.9 years (8.5 to 14.1). Further demographic as well as surgical data are depicted in Table 1. Overall mean iHOT and EQ5D scores at follow-up were 91.9 (SD 10.0) and 90.3 (SD 7.3), respectively.

The ROM was similar between Pemberton hips and non-affected hips. Both, the anterior as well as the posterior impingement sign were more common in Pemberton hips ($p = 0.046$ and $p = 0.046$, respectively) (Table 2).

At follow-up, LCE angles were slightly decreased in the Pemberton group ($p = 0.061$) whereas AI angles showed no difference ($p = 0.816$). Also, the prevalence of the crossover as well as the ischial spine sign did not differ between the groups ($p = 0.317$ and $p = 0.564$, respectively) (Table 3).

In the Pemberton group, five hips had signs of mild to moderate OA at follow-up (KL I or II), whereas in the non-operated group none of the hips did.

MRI-based mean acetabular version at the femoral head centre at follow-up was 18.59° (SD 6.96°) for the operated hips (n = 12) and 19.50° (SD 4.61°) for the non-operated hips (n = 8; $p = 0.974$). Mean version at the roof level was 0.80° (SD 7.09°) for the operated side and 3.73° (SD 6.7°) for the non-operated side ($p = 0.481$), while mean femoral version was 22.8° (SD 17.85°) and 17.84° (SD 8.3°), respec-

Table 2 Range of movement and impingement (Imp.) sign compared between operated and non-operated hips. A p-value of <0.05 indicates statistical significance (in italics).

	Operated	Non-operated	p-value*
Mean flexion (sd; range)	116.25 (12.08; 100 to 130)	120.00 (5.98; 110 to 130)	0.058
Mean abduction (sd; range)	39.58 (4.98; 30 to 45)	41.25 (13.30; 15 to 50)	0.435
Mean adduction (sd; range)	27.92 (10.10; 20 to 55)	22.50 (5.35; 15 to 30)	0.180
Mean internal rotation 90° (sd; range)	36.67 (13.20; 5 to 55)	39.38 (9.43; 30 to 55)	0.916
Mean internal rotation 0° (sd; range)	44.58 (16.02; 5 to 70)	42.50 (14.64; 30 to 70)	0.500
Mean external rotation 90° (sd; range)	36.67 (15.42; 5 to 70)	41.88 (7.99; 25 to 50)	0.606
Mean external rotation 0° (sd; range)	28.33 (12.67; 10 to 60)	26.88 (5.94; 20 to 60)	0.854
Imp. sign anterior, n/N (%)	6/12 (*50*)	1/8 (*12.5*)	*0.046*
Imp. sign posterior, n/N (%)	5/12 (*41.7*)	1/8 (*12.5*)	*0.046*

* Mann-Whitney U-test

Table 3 Radiographic measurements in operated and non-operated hips. A p-value of < 0.05 indicates statistical significance (in italics)

	Operated	Non-operated	p-value*
Mean LCE (sd; range)	25.48 (5.78; 16.4 to 36.5)	28.91 (4.63; 22.4 to 33.6)	0.061
Mean AI (sd; range)	6.50 (5.77; -2.3 to 15.3)	7.31 (3.74; -0.1 to 12.1)	0.816
Crossover sign, n/N (%)	7/12 (*58.3*)	4/8 (*50*)	0.317
Ischial spine sign, n/N (%)	7/12 (*58.3*)	2/8 (*25*)	0.564

LCE, lateral centre edge (angle); AI, acetabular index; * Mann-Whitney U-test

tively (p = 0.884). Alpha angles were similar between the Pemberton and the non-Pemberton groups in all positions, as were ASA angles. CCA angles were similar between Pemberton hips and non-affected hips except for the 12 o'clock position. Here, the non-affected hips showed an increased articular surface (p = 0.037) (Fig. 3).

Five patients were younger than six years at surgery (1.3 years to 6 years) and five patients were older (7.2 years to 11.5 years). Radiographic results and PROMs at follow-up were compared between these 'early childhood' and 'late childhood' cohorts (Table 4).

The prevalence of the anterior and posterior impingement sign was similar between the age groups (p = 0.149 and p = 0.432).

Radiographic analysis showed similar LCE and AI angles between the groups (p = 0.149 and p = 0.432). The crossover sign, meanwhile, was more common in the early childhood cohort (p = 0.048) and the prevalence of the ischial spine sign did not differ (p = 0.432).

In the MRI analysis, the acetabular as well as femoral version were similar between both cohorts. Also, there were no differences between the groups regarding both sphericity and coverage. There was a trend towards a decreased anteversion at the femoral head centre in the late childhood cohort when compared with the younger group (p = 0.214).

Function and quality of life were found to be comparable (p = 0.121 and p = 0.432, respectively) (Table 5).

Discussion

The Pemberton osteotomy was described as an incomplete pericapsular ilium osteotomy to modify the shape and radius of the acetabulum by hinging the horizontal branch of the triradiate cartilage.[2] By achieving adequate containment further improvement of osseous remodelling of the dysplastic acetabulum shall be supported.

Concerns have been raised about acetabular retroversion following osteotomies that improve anterolateral coverage of the hip. This issue has been observed after Salter osteotomies, however, there have also been studies that have discussed the potential of acetabular retroversion after a Pemberton osteotomy.[17,18]

Using conventional radiographs, Wang et al[17] found no difference in the vertical-center-anterior margin angle or the anterior acetabular head index. However, the weight-bearing zone acetabular index was decreased when compared with the contralateral, non-operated hips, suggesting increased anterior acetabular coverage.

In the study by Akiyama et al,[18] 37.5% of Pemberton hips had a positive crossover sign, which was significantly higher than an observed estimate of 10% in a group which received bracing only.

Major limitations of these studies, however, are the application of different methods to define acetabular retroversion and the lack of evaluation through contemporarily advanced imaging techniques for 3D assessment.[31] As conventional radiographs only give a 2D image and patient tilt can additionally influence the acetabular shape,[19] we decided to not only use conventional radiographs but also 3D assessment through MRI in order to obtain higher accuracy.

Using patient-specific 3D-printed models based on preoperative CT scans of 14 patients, Caffrey et al[32] performed mock surgeries, including Dega's, San Diego as well as Pemberton osteotomies. The Pemberton osteotomy was found to have 5.47° (sd 1.54°) of decreased version, albeit an increased coverage in the anterior acetabular region when compared with the preoperative status.

Since preoperative 3D imaging was lacking in our cohort of patients we compared the operated hips with
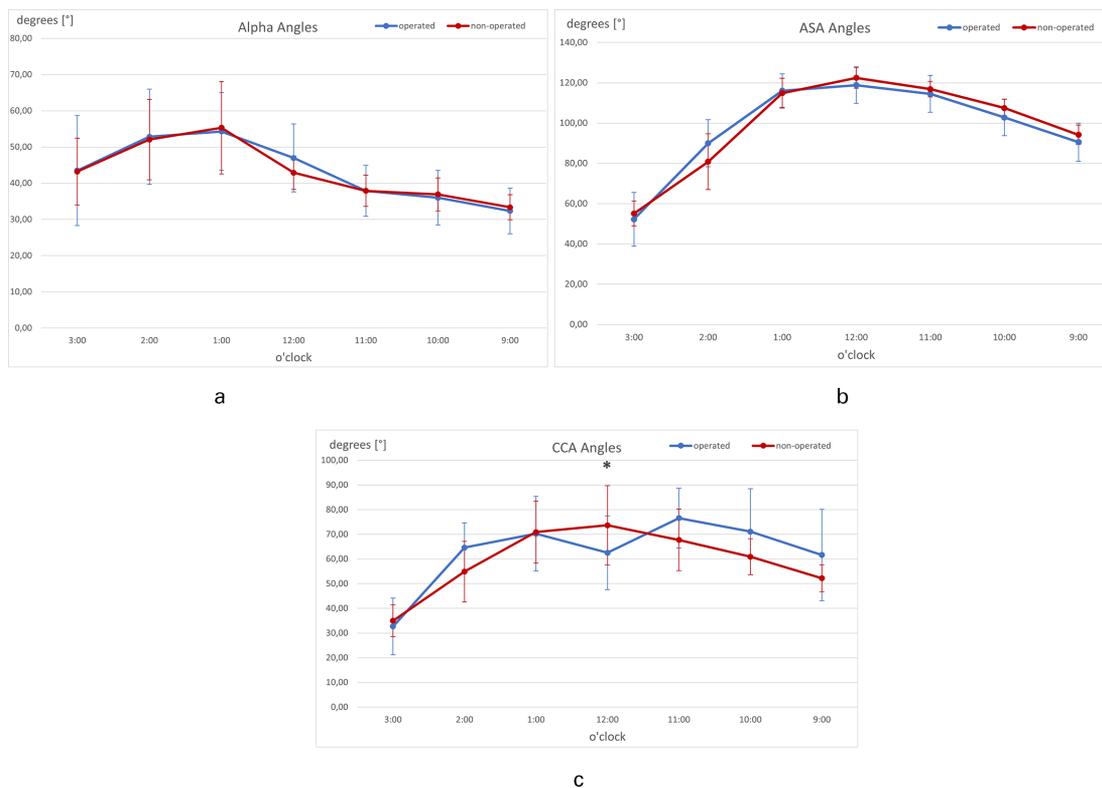
Fig. 3 Illustration of alpha angles (a), acetabular sector angle (ASA) (b) and cartilage covered area (CCA) angles (c) in relation to the acetabular position (9 o'clock to 3 o'clock, as explained in the 'Methods' section of this article). The blue curve depicts the operated hips, the red curve the non-operated hips. The respective angles are presented as mean with sd (error bars). An asterisk indicates a significant difference (p < 0.05) between the operated and non-operated side in the respective position.

Table 4 Age distribution of early childhood and late childhood cohort. A p-value of < 0.05 indicates statistical significance (in italics)

	Early childhood (age < 6 yrs)	Late childhood (age > 6 yrs)	p-value*
n	5	5	
Mean age at surgery, yrs (sd; range)	3.60 (2.03; 1.3 to 6.0)	9.84 (1.89; 7.2 to 11.5)	< 0.001
Mean age at FU, yrs (sd; range)	16.11 (2.24; 14.5 to 19.8)	21.34 (2.79; 15.8 to 23.6)	0.006
Mean duration of FU, yrs (sd; range)	12.51 (1.77; 9.7 to 14.0)	11.50 (1.67; 8.5 to 14.1)	0.339

FU, follow-up; * Mann-Whitney U-test

the contralateral sides, a study design that has also been used by other authors.[15,17]

Considering that seven out of 12 hips had a positive crossover sign and a positive ischial spine sign, there was a tendency towards acetabular retroversion in our cohort. However, conventional radiographic signs of retroversion were found in both, operated and non-operated hips, and were not different between the two. Also, MRI showed similar version and anterocranial coverage for the operated and non-operated side, however, retroversion was not as evident as with conventional radiographs. Only three out of 12 hips had a MRI-based version of < 15° at the femoral head centre, which can be regarded as mild retroversion. Ultimately, differentiating between a positive and a negative crossover sign (p = 0.212 and p = 0.372 for iHOT and EQ5D, respectively) as well as between a positive and a negative ischial spine sign (p = 0.287 and

p = 0.207, respectively) did not influence functional and quality of life scores. In summary, our findings suggest that a previous Pemberton osteotomy had only little long-term influence on the acetabular orientation in the sagittal plane.

Clinical impingement signs were more common with Pemberton hips when compared with the non-operated hips. This may be due to an increase in anterolateral coverage causing a focal pincer impingement. Although we had conventional radiographic signs suggesting these changes, we could not detect these changes in MRI in comparison with the non-operated side. Additional other co-factors such as an increased alpha angle possibly explaining the occurrence of the impingement sign were not detected. In the literature, both the anterior and posterior impingement test have displayed a high sensitivity for intraarticular FAI associated deformities but a low spec-

Table 5 Comparison of patient-reported outcomes (PROMs), range of movement, clinical signs and radiological as well as MRI measurements between early and late childhood cohort. A p-value of < 0.05 indicates statistical significance (in italics)

	Early childhood (age < 6 yrs)	Late childhood (age > 6 yrs)	p-value*
PROM, mean score (sd; range)			
iHOT	85.26 (12.84; 70.0 to 99.6)	96.56 (3.30; 90.8 to 98.5)	0.121
EQ5D	88.00 (10.95; 70 to 100)	91.86 (3.29; 90 to 98)	0.393
Mean range of movement, ° (sd; range)			
LCE	23.80 (5.61; 20.8 to 33.8)	26.69 (6.02; 16.4 to 36.5)	0.420
AI	6.76 (6.57; -2.3 to 15.3)	6.31 (5.67; -1.8 to 15.0)	0.920
Alpha 3	34.74 (7.32; 27.4 to 44.3)	49.77 (16.65; 36.8 to 85.4)	0.090
Alpha 2	47.30 (5.53; 37.5 to 50.8)	56.76 (15.95; 39.7 to 87.4)	0.237
Alpha 1	51.72 (8.88; 38.5 to 62.8)	56.09 (12.25; 42.0 to 77.1)	0.514
Alpha 12	44.60 (9.35; 34.8 to 55.0)	48.64 (9.76; 36.2 to 63.0)	0.488
Alpha 11	36.46 (8.65; 26.1 to 46.2)	38.90 (6.16; 30.5 to 45.1)	0.579
Alpha 10	33.18 (5.30; 26.2 to 39.5)	37.99 (8.58; 24.1 to 47.1)	0.296
Alpha 9	29.00 (6.72; 20.0 to 38.3)	34.70 (5.17; 27.9 to 41.1)	0.126
ASA 3	48.14 (13.17; 37.0 to 69.3)	55.09 (13.79; 31.0 to 68.7)	0.402
ASA 2	89.92 (9.87; 81.9 to 106.7)	89.99 (13.67; 61.0 to 104.0)	0.993
ASA 1	116.72 (3.47; 113.2 to 122.0)	115.56 (10.86; 94.0 to 124.6)	0.824
ASA 12	118.46 (6.13; 111.7 to 126.0)	119.07 (11.25; 96.0 to 132.3)	0.915
ASA 11	112.38 (8.84; 102.2 to 123.0)	115.99 (9.75; 96.6 to 127.9)	0.527
ASA 10	102.38 (7.37; 94.5 to 114.0)	103.01 (10.57; 82.0 to -113.5)	0.911
ASA 9	91.00 (9.50; 82.0 to 105.0)	90.17 (10.08; 71.0 to 105.0)	0.889
CCA 3	30.12 (10.29; 21.0 to 6.2)	34.51 (12.74; 14.6 to 52.5)	0.540
CCA 2	66.36 (12.68; 45.4 to 80.0)	63.36 (8.36; 52.9 to 71.6)	0.630
CCA 1	67.96 (13.14; 45.4 to 78.7)	71.89 (17.20; 49.0 to 93.5)	0.679
CCA 12	64.96 (11.61; 50.0 to 78.0)	60.80 (17.62; 32.4 to 81.0)	0.657
CCA 11	82.72 (14.08; 70.0 to 101.0)	72.13 (9.12; 58.1 to 79.0)	0.143
CCA 10	79.00 (14.96; 65.5 to 96.0)	65.46 (17.80; 42.0 to 99.0)	0.197
CCA 9	70.56 (22.34; 53.0 to 100.2)	55.20 (13.53; 31.9 to 70.0)	0.167
Anteversion roof	-1.14 (7.56; -11.4 to 9.0)	2.19 (6.97; -11.2 to 7.7)	0.449
Anteversion centre	21.64 (9.53; 6.2 to 30.0)	16.41 (3.87; 11.3 to 22.4)	0.214
Femoral torsion	18.20 (27.76; -11.4 to 46.0)	26.09 (6.33; 13.3 to 32.0)	0.564
Clinical signs, n/N (%)			
Imp. sign (anterior)	4/5 (*80*)	2/7 (28.6)	0.149
Imp. sign (posterior)	3/5 (*60*)	2/7 (28.6)	0.432
Crossover sign	5/5 (*100*)	2/7 (28.6)	*0.048*
Ischial spine sign	2/5 (*40*)	5/7 (71.4)	0.432

iHOT, International Hip Outcome Tool; EQ5D, EuroQol-5-Dimensions (score); LCE, lateral center edge (angle); AI, acetabular index; ASA, acetabular sector angle; CCA, cartilage covered area (angle); Imp., Impingement; * Mann-Whitney U-test

ificity.[33-35] Our analysis suggests that the positive anterior and posterior impingement signs may not be explained by morphological changes of the acetabulum but also by possible extraarticular impingement, scar formation or more patient sensitivity due to prior surgical intervention in our cohort.

While signs of OA were only found in Pemberton hips, it was mostly a mild OA (KL I). Only one hip showed signs of moderate OA (KL II). The presence of OA had no influence on function or quality of life, suggesting that the mild stages did not compromise patient well-being.

Finally, no major differences could be observed between patients, where surgery was performed below and over six years of age (Table 5, Fig. 4). Surprisingly, the crossover sign was less frequent in the late childhood cohort and also the anteversion was decreased in comparison with the younger group with similar anterocranial coverage. The frequency of the ischial spine sign did not differ between the age groups. It is widely acknowledged that the Pemberton osteotomy and comparable surgeries should be performed before the age of six years. Coleman[36] cautioned against the use of Pemberton osteotomy after the

age of six years due to the decreased remodelling time as well as the increased risk of dislocation due to dysplasia. Dora et al,[14] meanwhile, found a higher prevalence of acetabular retroversion after triple osteotomy in children older than six years. Akiyama et al[18] found a significantly higher prevalence of the crossover sign in addition to decreased centre-edge angles as well as increased AI angles in patients older than seven years and nine months of age when compared with children that were younger. Our results, although biased by the low sample size, suggest that the Pemberton osteotomy is a treatment option that might not necessarily be limited to very young children.

Whether based on these findings the Pemberton osteotomy should be favoured against the SIO, which can also be used for DDH and which has also been associated with postoperative retroversion,[13-16] remains up for discussion. To our knowledge, until now, no study has investigated acetabular version and orientation following SIO by using 3D imaging. Only when the true effects of this procedure are known can a recommendation be made.

Our study has several limitations. The first is the absence of pre- and directly postoperative MRI, mak-
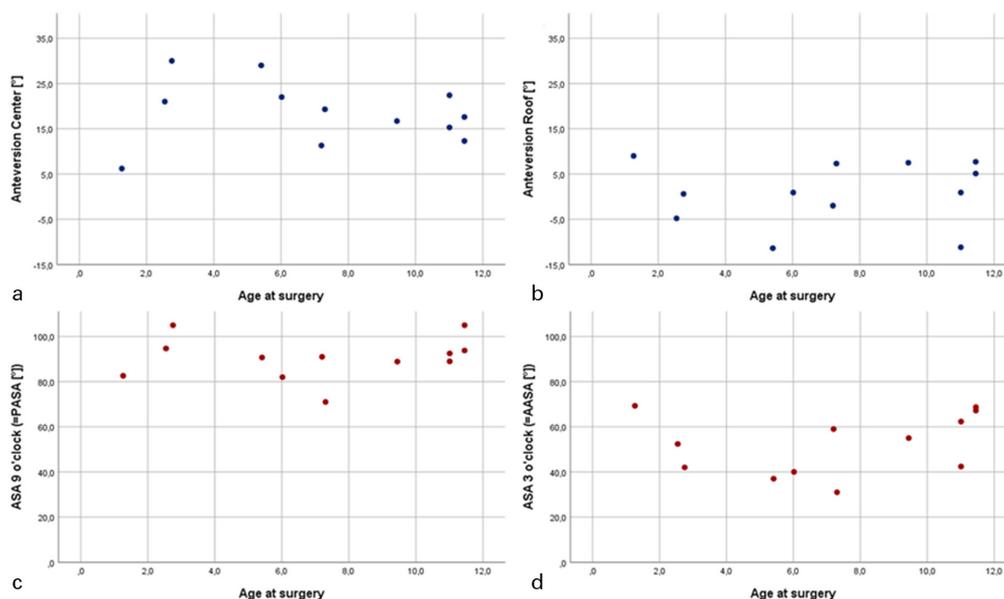
Fig. 4 MRI-based acetabular version (a, b) and coverage (c, d) in correlation with age. Dots represent operated hips. The horizontal axis depicts the age at surgery in years, the vertical axis the respective angle: a) anteversion at the center level; b) anteversion at the roof level; c) acetabular sector angle (ASA) at the 9 o'clock position represents coverage of the posterior wall; d) ASA at the 3 o'clock position represents coverage of the anterior wall (PASA, posterior ASA; AASA, anterior ASA).

ing a continuous follow-up during adolescence impossible. By using the contralateral, non-operated hip for comparison, we created a control group, which on one side may have some degree of the pathology while on the other mimics the patients' hip development at the best.

Secondly, our study and the statistical analysis suffers from the low sample size. Since two patients had bilateral surgery, the control group consists of only eight hips. Although comparable studies had similar sample sizes,[13,16-18] this fact may contribute to the fact we are lacking statistical significance for some MRI findings. In addition, since advanced imaging techniques have not been previously used in the follow-up of Pemberton patients, the comparison with other studies is limited.

Thirdly, our mean follow-up duration of 11.9 years (sd 1.7) is high, however, not sufficient in order to determine the long-term effect of the osteotomy.

Conclusion

In summary, we found no increased retroversion in patients after skeletal maturation, who had undergone previous Pemberton osteotomies. Although there were residual impingement signs as well as signs of the beginning of OA in a number of patients, long-term follow-up results were good to very good. Larger sample sizes and longer follow-ups would be needed in order to better comprehend the long-term effects of the surgery.

COMPLIANCE WITH ETHICAL STANDARDS

FUNDING STATEMENT

OA LICENCE TEXT

ETHICAL STATEMENT

ICMJE CONFLICT OF INTEREST STATEMENT
The authors have no conflict of interest to disclose.

AUTHOR CONTRIBUTIONS
PB: Research design, Acquisition of data, Analysis of data, Interpretation of data, Drafting of manuscript, Revision of manuscript.
SB: Acquisition of data, Analysis of data, Interpretation of data, Revision of manuscript.
AH: Analysis of data, Interpretation of data, Revision of manuscript.
FT: Research design, Analysis of data, Interpretation of data, Revision of manuscript.
KPG: Analysis of data, Interpretation of data, Revision of manuscript.
JG: Research design, Acquisition of data, Analysis of data, Interpretation of data, Drafting of manuscript, Revision of manuscript.

REFERENCES

1. **Woźniak Ł, Idzior M, Jóźwiak M.** Dega transiliac pelvic osteotomy for developmental hip dysplasia: a systematic review. *J Pediatr Orthop B* 2020;15:171-177.

2. **Pemberton PA.** Pericapsular osteotomy of the ilium for treatment of congenital subluxation and dislocation of the hip. *J Bone Joint Surg [Am]* 1965;47-A:65-86.

3. **Selberg CM, Chidsey B, Skelton A, Mayer S.** Pelvic osteotomies in the child and young adult hip: indications and surgical technique. *J Am Acad Orthop Surg* 2020;28:e230-e237.

4. **Grudziak JS, Ward WT.** Dega osteotomy for the treatment of congenital dysplasia of the hip. *J Bone Joint Surg [Am]* 2001;83-A:845-854.

5. **Salter RB.** Role of innominate osteotomy in the treatment of congenital dislocation and subluxation of the hip in the older child. *J Bone Joint Surg [Am]* 1966;48-A:1413-1439.

6. **Steel HH.** Triple osteotomy of the innominate bone. *J Bone Joint Surg [Am]* 1973;55-A:343-350.

7. **Tönnis D, Kalchschmidt K, Heinecke A.** Acetabular rotations y triple pelvic osteotomy by the Tönnis method. *Orthopade* 1998;27:733-742.

8. **Leunig M, Ganz R.** The Bernese method of periacetabular osteotomy. *Orthopade* 1998;27:743-750.

9. **Schramm M, Hohmann D, Radespiel-Troger M, Pitto RP.** The Wagner spherical osteotomy of the acetabulum. Surgical technique. *J Bone Joint Surg [Am]* 2004;86-A(suppl 1):73-80.

10. **Nakata K, Masuhara K, Sugano N, et al.** Dome (modified Chiari) pelvic osteotomy: 10- to 18-year followup study. *Clin Orthop Relat Res* 2001;389:102-112.

11. **Krieg AH, Hefti F.** Acetabuloplasty - the Dega and Pemberton technique. *Orthopade* 2016;45:653-658.

12. **Lequesne M.** Coxometry. Measurement of the basic angles of the adult radiographic hip by a combined protractor. *Rev Rhum Mal Osteoartic* 1963;30:479-485.

13. **Barnes JR, Thomas SR, Wedge J.** Acetabular coverage after innominate osteotomy. *J Pediatr Orthop* 2011;31:530-533.

14. **Dora C, Mascard E, Mladenov K, Seringe R.** Retroversion of the acetabular dome after Salter and triple pelvic osteotomy for congenital dislocation of the hip. *J Pediatr Orthop B* 2002;11:34-40.

15. **Kobayashi D, Satsuma S, Kinugasa M, Kuroda R, Kurosaka M.** Does Salter innominate osteotomy predispose the patient to acetabular retroversion in adulthood? *Clin Orthop Relat Res* 2015;473:1755-1762.

16. **Robb CA, Datta A, Nayeemuddin M, Bache CE.** Assessment of acetabular retroversion following long term review of Salter's osteotomy. *Hip Int* 2009;19:8-12.

17. **Wang CW, Wu KW, Wang TM, Huang SC, Kuo KN.** Comparison of acetabular anterior coverage after Salter osteotomy and Pemberton acetabuloplasty: a long-term followup. *Clin Orthop Relat Res* 2014;472:1001-1009.

18. **Akiyama M, Nakashima Y, Oishi M, et al.** Risk factors for acetabular retroversion in developmental dysplasia of the hip: does the Pemberton osteotomy contribute? *J Orthop Sci* 2014;19:90-96.

19. **Wassilew GI, Heller MO, Diederichs G, et al.** Standardized AP radiographs do not provide reliable diagnostic measures for the assessment of acetabular retroversion. *J Orthop Res* 2012;30:1369-1376.

20. **Reynolds D, Lucas J, Klaue K.** Retroversion of the acetabulum. A cause of hip pain. *J Bone Joint Surg [Br]* 1999;81-B:281-288.

21. **Siebenrock KA, Kalbermatten DF, Ganz R.** Effect of pelvic tilt on acetabular retroversion: a study of pelves from cadavers. *Clin Orthop Relat Res* 2003;407:241-248.

22. **Tönnis D, Heinecke A.** Acetabular and femoral anteversion: relationship with osteoarthritis of the hip. *J Bone Joint Surg [Am]* 1999;81-A:1747-1770.

23. **Goronzy J, Blum S, Hartmann A, et al.** Is MRI an adequate replacement for CT scans in the three-dimensional assessment of acetabular morphology? *Acta Radiol* 2019;60:726-734.

24. **Thorborg K, Roos EM, Christensen R, Petersen J, Hölmich P.** The iHOT-33: how valid is it? *Arthroscopy* 2012;28:1194-1195.

25. **Balestroni G, Bertolotti G.** EuroQol-5D (EQ-5D): an instrument for measuring quality of life. *Monaldi Arch Chest Dis* 2012;78:155-159.

26. **Wiberg G.** Studies on dysplastic acetabula and congenital subluxation of the hip joint with special references to the complication of osteoarthritis. *Acta Chir Scand Scandinavica* 1939; 83:58.

27. **Lequesne M, Bellaïche L.** Anterior femoroacetabular impingement: an update. *Joint Bone Spine* 2012;79:249-255.

28. **Kellgren JH, Lawrence JS.** Radiological assessment of osteo-arthrosis. *Ann Rheum Dis* 1957;16:494-502.

29. **Anda S, Terjesen T, Kvistad KA, Svenningsen S.** Acetabular angles and femoral anteversion in dysplastic hips in adults: CT investigation. *J Comput Assist Tomogr* 1991;15:115-120.

30. **Sutter R, Dietrich TJ, Zingg PO, Pfirrmann CW.** Assessment of femoral antetorsion with mri: comparison of oblique measurements to standard transverse measurements. *AJR Am J Roentgenol* 2015;205:130-135.

31. **Ippolito E.** CORR Insights(®): does salter innominate osteotomy predispose the patient to acetabular retroversion in adulthood? *Clin Orthop Relat Res* 2015;473:1763-1764.

32. **Caffrey JP, Jeffords ME, Farnsworth CL, Bomar JD, Upasani VV.** Comparison of 3 pediatric pelvic osteotomies for acetabular dysplasia using patient-specific 3d-printed models. *J Pediatr Orthop* 2019;39:e159-e164.

33. **Reiman MP, Mather RC III, Cook CE.** Physical examination tests for hip dysfunction and injury. *Br J Sports Med* 2015;49:357-361.

34. **Martin RL, Irrgang JJ, Sekiya JK.** The diagnostic accuracy of a clinical examination in determining intra-articular hip pain for potential hip arthroscopy candidates. *Arthroscopy* 2008;24:1013-1018.

35. **Nepple JJ, Prather H, Trousdale RT, et al.** Clinical diagnosis of femoroacetabular impingement. *J Am Acad Orthop Surg* 2013;21(suppl 1):S16-S19.

36. **Coleman SS.** The incomplete pericapsular (Pemberton) and innominate (Salter) osteotomies; a complete analysis. *Clin Orthop Relat Res* 1974;98:116-123.