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Prognostic value of bone resorption pattern in the anterior portion of the femoral head in Legg–Calvé–Perthes disease

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Abstract

Purpose: To examine whether differences in bone resorption patterns in the anterior portion of the femoral head correlate with the prognosis of Legg–Calvé–Perthes disease.

Methods: Seventy-eight patients with unilateral Legg–Calvé–Perthes disease, who were diagnosed after 6.0 years of age, underwent the Salter innominate osteotomy from 1987 to 2013, and were followed up to skeletal maturity. The anterior bone resorption pattern of the femoral head was evaluated from a frog-leg lateral hip radiograph made in the middle of the fragmentation period, and classified into two types, an epiphysis-preserved type (P) and a physis-disrupted type (D). The correlation between the type of bone resorption and the Stulberg outcome was analyzed.

Results: The Stulberg outcomes were grade I for 9 patients, grade II for 31, grade III for 35, and grade IV for 3, with a mean follow-up period of 8.3 ± 2.7 years. Fifty-one patients demonstrated the type P hips and 27 did the type D hip. In a subset analysis of patients with the modified lateral pillar group-B hips in the younger group (6.0–8.9 years of age at diagnosis), the percentages of the favorable and unfavorable outcomes significantly differed between the two types ($p = 0.013$). Anteroposterior enlargement of the affected femoral head was significantly greater in the type D hips than the type P hips ($p = 0.014$).

Conclusion: Unfavorable hip morphology at skeletal maturity can be predicted in patients with the lateral pillar group-B hips by focusing on bone resorption patterns of the anterior portion of the femoral head.

Level of evidence: Level III, prognostic study.

Keywords: Legg–Calvé–Perthes disease, anterior bone resorption, Stulberg classification, modified lateral pillar classification

Introduction

Legg–Calvé–Perthes disease (LCPD) is a pediatric form of osteonecrosis of the femoral head that has been attributed to interruption of local blood supply of unknown etiology. Although LCPD is considered a self-repairing condition, delayed diagnosis and inappropriate management can readily produce enlargement and deformation of the femoral head that increases the likelihood of degenerative osteoarthritis in adulthood.[1,2] Several clinical and radiographic factors have been utilized to predict hip morphology at skeletal maturity.[3,4] Of those, age at the onset of the disease is proved to be a potent prognostic factor, with children at 9.0 years or more of age and those at 6.0 years or less having poor and good prognoses, respectively. The timing of initiation of containment therapy matters especially for patients whose disease onset is older than 8.0 years, because the extrusion of the femoral head invariably occurs in the early phase of the disease; hence, proper containment should be offered to older patients as soon as

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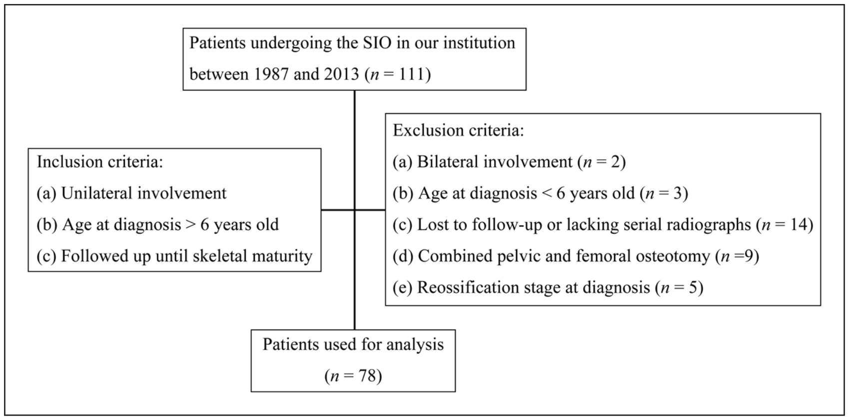

Figure 1. A flowchart of the case selection process.

the disease is diagnosed. The modified lateral pillar (LP) classification, generally assumed to reflect the extent of osteonecrosis, has represented a reliable prognostication system,[5] with the group-A femoral head expected to achieve a good spherical and congruent hip, whereas the group-B/C border or group-C tending to become a non-spherical and/or incongruent hip. The LP group-B hips, in contrast, belong to an intermediate category that can give better results than the group-B/C border or group-C hips but do not necessarily provide a favorable prognosis even in younger children irrespective of whether they undergo non-operative or operative treatments.[6] As children with the group-B hips account for the majority of LCPD patients, identification of possible determinants of unfavorable results in this group has profound clinical significance in the management of LCPD.

Hip morphology at skeletal maturity, commonly classified with the use of the Stulberg classification, has been determined using both anteroposterior and lateral hip radiographs in terms of the sphericity of the femoral head and congruency of the acetabulum;[5] a favorable result of the Stulberg grade I or II hips should meet such a criterion that a radius of a best-fit circle drawn to match the surface of the femoral head fits within 2 mm on both views. Accordingly, it is reasonable to assume that, even in the LP group-B and adequately contained hips, significant changes in the direction and/or capacity of the epiphyseal growth in the anterior portion of the femoral head would produce unfavorable results of the Stulberg III or more hips. A previous study investigating the pathogenesis of capital femoral epiphysis in a piglet model of ischemic proximal femoral osteonecrosis has revealed that growth disturbance of the femoral neck could develop in a few animals exhibiting metaphyseal radiolucency on radiographs and interruption and curvature of the growth plates on histology.[7] The purpose of this study was to examine, especially in the LP group-B hips, whether differences in bone resorption patterns of the anterior portion of the femoral head correlated with the Stulberg outcome in a homogeneous cohort of unilateral LCPD treated with Salter innominate osteotomy (SIO) at the earlier stage of the disease.

Materials and methods

Study design

This is a retrospective study approved by the institution review board of an authors' affiliated institution. We comprehensively reviewed medical records and radiographic images of children diagnosed with LCPD who had undergone the SIO in our institution between 1987 and 2013. Inclusion criteria included a case of unilateral involvement and 6 years of age or more at diagnosis with follow-up until skeletal maturity. Exclusion criteria included a hip that had already reached the reossification stage at diagnosis according to the modified Waldenström classification,[8] a hip treated with a combined pelvic and femoral osteotomy for a hinged abduction, and a case lacking serial radiographs made throughout the clinical course of LCPD (Figure 1). We have adopted and utilized only SIO as a containment method for all patients aged 6 years or more at diagnosis in the avascular necrosis or early fragmentation stage since 1987.[9] Our indications for SIO have exclusively depended on age and disease stage at diagnosis. We have not considered other imaging findings including the modified LP classification when determining treatment options for LCPD. We have not adopted a "wait and classify" approach[2] in fear of an accidental collapse of brittle capital epiphysis during a waiting period. When patients and their parents disagreed with our policy, they were immediately transferred to other dedicated facilities for conservative treatment with non-ambulatory and/or ambulatory abduction bracing.[10]

Surgical procedures and pre-and post-operative protocol

Immediately after the definite diagnosis of LCPD, patients were hospitalized to undergo skin traction of the lower limbs to reduce intracapsular synovitis. Patients underwent the SIO after restoring 30 degrees or more of hip abduction. Pelvic osteotomy was performed by standard procedures as described previously.[10] To reduce the intracapsular pressure, the adductor longus was released through a small inguinal incision, and intramuscular tenotomy of the psoas major was performed through the window to the pelvic brim that was created medially to the medial aspect of the ilium. Postoperatively, hips were immobilized in one and one-half hip spica cast for 3 weeks, followed by aggressive range-of-motion exercise. Patients were allowed partial weight-bearing up to 10 kg with crutches 8 weeks after the osteotomy. Only when the affected hips entered the reossification stage, patients were allowed full weight-bearing. All school-aged patients were examined every long holiday twice or three times a year until skeletal maturity, and patients and their parents were usually requested to visit one or two more times during the school day until implant removal. This examination schedule corresponds to 3- or 4-month intervals during the active stage of the disease and afterward at least 6-month intervals.

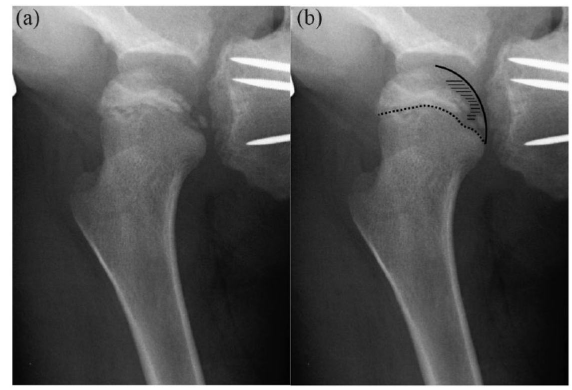

Figure 2. A physis-preserved type (P) pattern of the anterior bone resorption. (a) This type is defined as a hip with the anterior portion of bone resorption restricted to the capital epiphysis. (b) Anterior epiphyseal line (dashed line) can be traced to the anterior edge of the widened metaphysis.

Radiographic evaluation

The modified LP classification was determined from an anteroposterior radiograph of the hip made in the middle of the fragmentation period, with 6 cases classified using radiographs made before the SIO and the remaining 72 after that. The Stulberg classification was assessed from a pair of anteroposterior and frog-leg lateral hip radiographs made at skeletal maturity.[5] The pattern of bone resorption in the anterior portion of the femoral head was evaluated from a frog-leg lateral hip radiograph made in the middle of the fragmentation period, on which a best-fit circular arc was drawn from the most anteromedial point of the contour of the unabsorbed epiphysis to the anterior edge of the widened metaphysis to define an anterior portion of bone resorption. Next, an anterior epiphyseal line, usually demarcated from radiolucency by residual calcified bones of the epiphysis and the intact metaphysis, was drawn along a posterior one to the point where it intersects with the arc (Figure 2). When an anterior one could not be traced from a posterior one, a best-fit, smoothly curved line was similarly drawn (Figure 3). Then, we classified the anterior portion of bone resorption into two types: a physis-preserved type (P) and a physis-disrupted type (D). The former was defined as a hip with the anterior portion of bone resorption restricted to the capital epiphysis. In this type, the anterior epiphyseal line, gently curving and, in some cases, a little widening caudally, can be traced to the anterior edge of the widened metaphysis (Figure 2). In contrast, the latter was defined as a hip with the anterior portion of bone resorption appearing to span from the epiphysis to the metaphysis. In this type, the anterior epiphyseal line appears to be interrupted in the middle of the physis, and the best-fit line runs through the anterior portion of bone resorption (Figure 3). Two investigators (K.M. and Y.K.) independently evaluated all sets of anteroposterior and frog-leg lateral hip radiographs made in the fragmentation period and at skeletal maturity to assign the patterns of bone resorption in the anterior portion of the femoral head, the groups of the modified LP classification,[11] and the grades of the Stulberg classification.[5] In cases of disagreement on them, the final consensus was determined through open discussion. The enlargement ratio of the femoral head was calculated using the anteroposterior and frog-leg lateral hip radiographs made at skeletal maturity by dividing the difference of the widest diameter of the femoral head between the affected side and contralateral side by the widest diameter of the

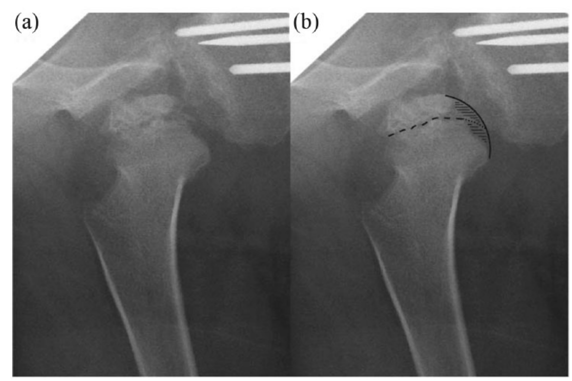

Figure 3. A physis-disrupted type (D) pattern of the anterior bone resorption. (a) This type is defined as a hip with the anterior portion of bone resorption appearing to span from the epiphysis to the metaphysis. (b) An anterior epiphyseal line appears to be interrupted in the middle of the physis (dashed line), and the best-fit line (dotted line) runs through the anterior portion of bone resorption.

contralateral side for each view.[12] The anterior tilt angle of the capital femoral epiphysis was determined from the frog-leg lateral hip radiograph made at the time close to the capital femoral physeal closure by measuring the angle formed between the line perpendicular to the femoral shaft axis and the line connecting each of the anterior and posterior edges of the epiphyseal growth plate (Figure 4).

Statistical analysis

Based on numerous previous reports demonstrating that age at onset had a significant prognostic value with respect to the Stulberg outcome, patients were classified into two groups, a younger group (6.0–8.9 years of age at diagnosis) and an older group (9.0 years of age or more at diagnosis) and analyzed separately. We analyzed data using the SPSS Statistics version 27 (IBM, Tokyo, Japan). Fisher's exact or an unpaired *t*-test test was used to compare categorical or continuous variables, respectively. The kappa statistics were used to analyze the degree of agreement for categorical variables between the two observers. According to a previous study, the LP classifications were coded as 1 for A, 2 for B, 2.5 for B/C, and 3 for C, and the Stulberg classifications were coded as 2 for I or II, 3 for III, and 4 for IV by considering clinical relevance and significance of these classification systems.[5] Resultant kappa coefficients were interpreted based on the guidelines proposed by Landis and Koch,[13] with a value of 0.61–0.80 indicating substantial agreement and 0.81–1.00 almost perfect agreement. A p-value < 0.05 was considered statistically significant. Values are expressed as mean value ± standard deviation.

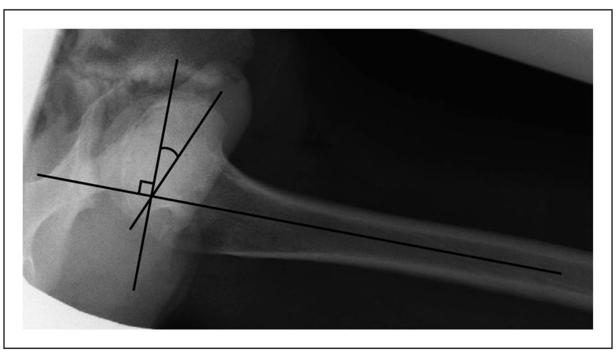

Figure 4. Anterior tilt angle of the capital femoral epiphysis. The angle is defined as one formed between the femoral shaft axis and the line connecting each of the anterior and posterior edges of the epiphyseal growth plate.

Results

A total of 78 patients with 78 affected hips met the inclusion criteria and were analyzed, with 37 children affected on the right side and 41 on the left side. There were 64 boys and 14 girls. The mean age at diagnosis was 7.9 ± 1.3 years (range = 6.0–11.8 years). At diagnosis, 65 hips were in the Waldenström stage I, and 13 hips were in stage II. The mean follow-up period was 8.3 ± 2.7 years (range = 4.0–15.8 years). Across all patients, 4 children were classified as having the LP group-A hip, 34 as the group-B, 28 as the group-B/C border, and 12 as the group-C. The Stulberg outcomes were graded as I for 9 patients, II for 31, III for 35, and IV for 3. With regard to the bone resorption pattern in the anterior portion of the femoral head, 51 hips demonstrated a physis-preserved type P and 27 did a physis-disrupted type D at the mid-fragmentation stage. There were 64 children in the younger group and 14 in the older group. Patients' characteristics and radiographic outcomes of the two age groups are shown in Table 1. A significant difference was observed in the proportion of the favorable (Stulberg grade I or II) versus unfavorable (Stulberg grade III or IV) outcomes between

Table 1. Comparisons of patients' characteristics and radiographic outcomes by age group.[a]

	Younger group (n = 64)	Older group (n = 14)	p
Age at diagnosis (years)	7.4 ± 0.8	10.0 ± 0.8	<0.0001
Sex: boy	51 (80%)	13 (93%)	0.44
Laterality: right	30 (47%)	7 (50%)	1.0
Anterior resorption pattern	P: 45 (70%) D: 19 (30%)	P: 6 (43%) D: 8 (57%)	0.066
Lateral pillar classification	A: 4 (6%) B: 26 (41%) B/C: 24 (37%) C: 10 (16%)	A: 0 (0%) B: 8 (57%) B/C: 4 (29%) C: 2 (14%)	0.79
Age at last follow-up	16.0 ± 2.7	17.1 ± 2.5	0.066
Follow-up period	8.5 ± 2.7	7.0 ± 2.5	0.044
Stulberg outcome[b]	Favorable: 38 (59%) Unfavorable: 26 (41%)	Favorable: 2 (14%) Unfavorable: 12 (86%)	0.002

[a]The values are given as number (%) or mean value ± standard deviation.
[b]Favorable—grades I and II; unfavorable—grades III and IV.

Table 2. Distribution of numbers of patients according to the lateral pillar classification by type of anterior bone resorption and age group.

Anterior resorption pattern	Younger group*				Older group**			
	A	B	B/C border	C	A	B	B/C border	C
Type P	3	20	15	7	0	2	2	2
Type D	1	6	9	3	0	6	2	0

*$p=0.76$; **$p=0.15$.

Table 3. Comparisons of radiographic measurements by Stulberg outcome.[a]

	Favorable outcome ($n=40$)[b]	Unfavorable outcome ($n=38$)[b]	p
Enlargement ratio of the femoral head (%)			
Anteroposterior direction	6.0 ± 4.5	16.6 ± 8.2	<0.001
Mediolateral direction	6.0 ± 4.2	17.4 ± 8.0	<0.001
Anterior tilting of the epiphysis (°)			
Affected side	15.5 ± 11.1	24.4 ± 8.7	<0.001
Unaffected side	3.9 ± 6.6	2.3 ± 6.3	0.3

[a]The values are given as mean value ± standard deviation.
[b]Favorable—grades I and II; unfavorable—grades III and IV.

Table 4. Comparisons of radiographic outcomes and measurements by anterior resorption pattern in the younger patients with the LP group-B hips.[a]

	Type P ($n=20$)	Type D ($n=6$)	p
Stulberg outcome[b]	Favorable: 18 (90%) Unfavorable: 2 (10%)	Favorable: 2 (33%) Unfavorable: 4 (67%)	0.013
Enlargement ratio of the femoral head (%)			
Anteroposterior direction	5.6 ± 4.4	12.4 ± 8.5	0.014
Mediolateral direction	6.1 ± 5.7	17.2 ± 16.1	0.014
Anterior tilting of the epiphysis (°)			
Affected side	15.7 ± 12.9	21.0 ± 8.9	0.35
Unaffected side	2.6 ± 6.7	4.7 ± 5.0	0.48

LP: lateral pillar.
[a]The values are given as number (%) or mean value ± standard deviation.
[b]Favorable—grade I and II; unfavorable—grade III and IV.

the younger and older groups ($p=0.002$). No patient fell into a Stulberg V outcome. The percentages of the type P and D hips were comparable between the younger and older groups ($p=0.066$). The distribution of numbers of patients in each group of the LP classification did not significantly differ between the P and D types (Table 2; $p=0.76$ for the younger group and $p=0.15$ for the older group). Significant enlargement of the femoral head was observed in both directions in patients with favorable Stulberg outcomes compared to those with unfavorable Stulberg outcomes (Table 3; $p<0.001$). Anterior tilting of the epiphysis was greater in the affected hips with favorable outcomes than those with unfavorable outcomes ($p<0.001$) at nearly skeletal maturity. In a subset analysis of the younger patients with the LP group-B hips ($n=26$, Table 4), the proportions of the favorable and unfavorable outcomes significantly differed between the P and D types ($p=0.013$), with all but two patients with type P hips resulting in the Stulberg I or II outcomes (90%) whereas all but two patients with type D hips doing in the Stulberg III or IV outcomes (67%). The enlargement ratio of the femoral head was significantly larger in the type D hips than the type P hips in both directions ($p=0.014$). The anterior tilt angle of the epiphysis tended to be larger in the type D hips than the type P hips at nearly skeletal maturity, although the difference did not reach statistical significance ($p=0.35$). In another subset analysis of the patients with the LP group-B hips in the older group ($n=8$), the Stulberg outcomes did not significantly differ between the P and D types ($p=1.0$). The kappa coefficients for interobserver correlation were 0.77 for the anterior bone resorption pattern of the femoral head, 0.79 for the modified LP classification, and 0.82 for the Stulberg classification, ranging from substantial to almost perfect agreement.

Discussion

The primary finding of this study represents the specification of a radiographic pattern that can predict the unfavorable outcome of the Stulberg grade III or IV hip in the younger LCPD patients classified as having the LP group-B hips using the frog-leg lateral view made at the mid-fragmentation stage of the disease. Although the majority of patients with LCPD are classified as having the LP group-B hips that generally produce the favorable outcome of the Stulberg grade I or II hip irrespective of treatment methods,[11] a subset of the patients accounting for nearly 20% of the LP group-B hips falls into the Stulberg grade III or IV hip even in the younger patients,[6] implicating the presence of other prognostic factors that cannot be properly addressed by the conventional concept of containment of the lateral portion of the femoral head within the acetabulum.

The consensus on the primary goal of the management for LCPD has been the restoration of the spherical femoral head at skeletal maturity. A spherical object is naturally imaged as a circle regardless of which direction it is projected including anteroposterior and lateral views, based on which hips with minor and moderate ellipsoidal deformity of the femoral head have been categorized as the Stulberg grade II and III hip, respectively.[5] Even though the degree of femoral head deformity at skeletal maturity has been considered to largely depend on that of collapse at the lateral one-fourth of the capital femoral epiphysis during the fragmentation stage,[6] any factor that can elongate the diameter of the femoral head in the anteroposterior direction could deteriorate the sphericity of the femoral head, thereby it is reasonable to consider them as complementary prognostic factors for such an intermediate group of the LP group-B hips. We, therefore, paid attention to the mode of bone resorption in the anterior portion of the femoral head. Obviously, decent containment of the hip with a surgical or non-surgical method should be undertaken by the early fragmentation stage because decreased acetabular coverage and mechanical strength of the affected femoral head rapidly deteriorate during the fragmentation stage of the disease. We consider the SIO an appropriate procedure because it can restrain lateralization of the femoral head by shifting the center of the femoral head caudally and medially.[14]

A precise description would be impossible as to what occurred in the anterior portion of the femoral head in the type P and D hips because we cannot harvest necrotic bone specimens from living individuals. A previous study investigating the pathogenesis of metaphyseal radiolucent changes in a piglet model of ischemic proximal femoral osteonecrosis has revealed that interruption and curvature of the growth plates toward the metaphysis developed in 10% of the animals that exhibited a focal area of radiolucency spanning from the metaphysis into the epiphysis just above the proximal femoral physis on radiographs.[7] The femoral neck was significantly shorter in these animals with metaphyseal radiolucent changes than those without them, reflecting impaired elongation capacity of the physis caused by actual damage. Although histologically unproven, the anterior physis of the capital femoral epiphysis in the type D hips is thought to bend more strongly toward the metaphysis and face more anteriorly than that in the type P hips, resulting in the widening of the metaphysis in the anteroposterior direction. Differences in the growth capacity between impaired anterior and preserved posterior parts of the physis can be partly responsible for the misshapen femoral head. The greater anterior tilt angle of the capital femoral epiphysis in some of the type D hips may deteriorate the degree of anterior containment of the femoral head within the acetabulum, possibly failing to suppress anteroposterior enlargement of the femoral head during the reossification and healing stages.

Previous studies have discussed the relationship between the degree of physeal injury and the severity and/or prognosis of LCPD. The growth plate involvement (GPI) index, determined with biplanar radiographs at the stage of maximum fragmentation, has been proposed as a useful prognostic factor in patients with LCPD, with an increasing value of the index correlated to a worse prognosis of final radiographic outcomes.[15,16] The index, however, seems not to have the prognostic ability enough to replace the LP classification system because it showed a linear increase with disease progression of the modified Waldenström stages. We doubt that the GPI index reflects genuine physeal damage because the increasing index score of the GPI was not significantly associated with decreasing femoral neck length. A small difference in mean GPI index score between the Stulberg grade II and III hips may make reproducible prediction difficult between the two groups at the mid-fragmentation stage.

How can we handle the type D hips that become evident at the mid-fragmentation stage following the SIO performed at the earlier stage? For patients with poor prognosis in terms of age and severity, femoral varus and flexion osteotomy termed rotational open-wedge osteotomy (ROWO) coupled with non-weight bearing (NWB) has been shown to produce favorable outcomes compared to NWB alone by moving the viable posterolateral segment anteromedially.[17,18] For the LP group-B hips with the type D pattern, however, the ROWO may be unsuitable to perform because proximal femoral flexion osteotomy could attenuate anterior containment of the femoral head within the acetabulum in those hips. Instead, the addition of derotation and/or extension maneuver may be a promising adjunct to pelvic osteotomy partly because a high proportion of excessive anteversion, which can lead to decreased acetabular coverage, was observed at later stages of the disease in the affected hips.[19] Given the previous knowledge that less varus angulation was associated with a greater probability of obtaining a Stulberg grade I or II outcome for the LP-B hips,[20] careful considerations may be required to determine whether varus correction should be added to the osteotomy. Gradual correction of the asymmetric growth of the physis seems to be an alternative approach to obtaining a more spherical femoral head in selected patients. Selective hemiepiphysiodesis of the healthy physis in the posteroinferior quadrant of the capital femoral epiphysis with a 3.2-mm cannulated drill bit has shown to suppress an ellipsoidal process of the femoral head in cases with physeal angulation during the reossification stage.[21] Another experimental investigation demonstrated that multiple epiphyseal drilling with a 2-mm smooth K-wire stimulated bone healing without a significant growth disturbance in a piglet model of ischemic osteonecrosis.[22] Taken together, the combined use of hemiepiphysiodesis of the posterior physis and multiple epiphyseal drilling focusing on the anterior curved physis might have a potent synergistic effect on the restitution of a greater spherical femoral head in the type D hips.

This study has the following limitations. First, due to its retrospective nature, hip position and projection setting were not standardized when taking radiographs of the hip joint. This could affect discrimination of the mode of bone resorption and measurements of the angles. Second, strict adherence to partial weight-bearing up to 10 kg was difficult to practice postoperatively for some of the early school-age patients. Differences in compliance with weight-bearing restrictions during the fragmentation stage may affect the Stulberg outcomes. Third, we could not draw firm conclusions regarding prognostic prediction of LCPD made using bone resorption patterns of the anterior portion of the femoral head because of a limited number of the younger patients with the LP-group B hips. Finally, we analyzed only the patients treated with the SIO, not a femoral varus osteotomy (FVO) in this study. The postoperative positional relationship between the anterior aspect of the femoral head and the weight-bearing area of the acetabulum differs between the SIO and FVO. In addition, since there has been some evidence indicating that FVO can bypass fragmentation of the capital femoral epiphysis, our results may apply to only patients undergoing the SIO at an early stage. In conclusion, when treated with the SIO, unfavorable outcomes can be predicted in patients with the LP group-B hips, the majority of LCPD patients with an intermediate prognosis, by focusing on the bone resorption patterns of the anterior portion of the femoral head at the stage of maximum fragmentation using a frog-leg hip lateral radiograph. Our findings should have important implications when taking measures necessary to preserve the sphericity of the femoral head for a subset of patients with the LP group-B hips treated with the SIO at the earlier stage of the disease.

Author contributions

K.M. contributed to the final approval of the version to be published, conceptualization of the study, acquisition of data, statistical analysis, analysis and interpretation of data, and drafting the work or revising it critically for important intellectual content. Y.K. contributed to the final approval of the version to be published, acquisition of data, statistical analysis, and revising the work critically for important intellectual content. M.M. contributed to the final approval of the version to be published, acquisition of data, statistical analysis, and drafting the work or revising it critically for important intellectual content. S.I. contributed to the final approval of the version to be published, conceptualization of the study, and revising the work critically for important intellectual content.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The study was approved as a retrospective study by our institutional review board (IRB 2018-0011).

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Informed consent

Informed consent was not obtained from subjects in this retrospective study.

References

1. Kim HK. Pathophysiology and new strategies for the treatment of Legg-Calve-Perthes disease. *J Bone Joint Surg Am* 2012; 94(7): 659–669.
2. Kim HK and Herring JA. Pathophysiology, classifications, and natural history of Perthes disease. *Orthop Clin North Am* 2011; 42(3): 285–295, v.
3. Cheng JC, Lam TP and Ng BK. Prognosis and prognostic factors of Legg-Calve-Perthes disease. *J Pediatr Orthop* 2011; 31(2 Suppl.): S147–S151.
4. Wiig O, Terjesen T and Svenningsen S. Prognostic factors and outcome of treatment in Perthes' disease: a prospective study of 368 patients with five-year follow-up. *J Bone Joint Surg Br* 2008; 90(10): 1364–1371.
5. Herring JA, Kim HT and Browne R. Legg-Calve-Perthes disease. Part I: classification of radiographs with use of the

modified lateral pillar and Stulberg classifications. *J Bone Joint Surg Am* 2004; 86(10): 2103–2120.

6. Herring JA, Kim HT and Browne R. Legg-Calve-Perthes disease. Part II: prospective multicenter study of the effect of treatment on outcome. *J Bone Joint Surg Am* 2004; 86(10): 2121–2134.
7. Kim HK, Skelton DN and Quigley EJ. Pathogenesis of metaphyseal radiolucent changes following ischemic necrosis of the capital femoral epiphysis in immature pigs. *J Bone Joint Surg Am* 2004; 86(1): 129–135.
8. Hyman JE, Trupia EP, Wright ML, et al. Interobserver and intraobserver reliability of the modified Waldenstrom classification system for staging of Legg-Calve-Perthes disease. *J Bone Joint Surg Am* 2015; 97(8): 643–650.
9. Kitakoji T, Hattori T, Kitoh H, et al. Which is a better method for Perthes' disease: femoral varus or Salter osteotomy? *Clin Orthop Relat Res* 2005(430): 163–170.
10. Kaneko H, Kitoh H, Mishima K, et al. Comparison of surgical and nonsurgical containment methods for patients with Legg-Calve-Perthes disease of the onset ages between 6.0 and 8.0 years: Salter osteotomy versus a non-weight-bearing hip flexion-abduction brace. *J Pediatr Orthop B* 2020; 29(6): 542–549.
11. Kollitz KM and Gee AO. Classifications in brief: the Herring lateral pillar classification for Legg-Calve-Perthes disease. *Clin Orthop Relat Res* 2013; 471(7): 2068–2072.
12. Rowe SM, Moon ES, Song EK, et al. The correlation between coxa magna and final outcome in Legg-Calve-Perthes disease. *J Pediatr Orthop* 2005; 25(1): 22–27.
13. Landis JR and Koch GG. The measurement of observer agreement for categorical data. *Biometrics* 1977; 33(1): 159–174.
14. Kitoh H, Kaneko H and Ishiguro N. Radiographic analysis of movements of the acetabulum and the femoral head after Salter innominate osteotomy. *J Pediatr Orthop* 2009; 29(8): 879–884.
15. Domzalski ME, Inan M, Guille JT, et al. The proximal femoral growth plate in Perthes disease. *Clin Orthop Relat Res* 2007; 458: 150–158.
16. Park KW, Rejuso CA, Garcia RA, et al. Extent of physeal involvement in Legg-Calve-Perthes disease. *Int Orthop* 2014; 38(11): 2303–2308.
17. Atsumi T and Yoshiwara S. Rotational open wedge osteotomy in a patient aged older than 7 years with Perthes' disease—a preliminary report. *Arch Orthop Trauma Surg* 2002; 122(6): 346–349.
18. Nakamura N, Inaba Y, Machida J, et al. Rotational open-wedge osteotomy improves treatment outcomes for patients older than eight years with Legg-Calve-Perthes disease in the modified lateral pillar B/C border or C group. *Int Orthop* 2015; 39(7): 1359–1364.
19. Novais EN, Nunally KD, Ferrer MG, et al. Asymmetrically increased femoral version with high prevalence of moderate and severe femoral anteversion in unilateral Legg-Calve-Perthes disease. *J Child Orthop* 2021; 15(5): 503–509.
20. Kim HK, da Cunha AM, Browne R, et al. How much varus is optimal with proximal femoral osteotomy to preserve the femoral head in Legg-Calve-Perthes disease? *J Bone Joint Surg Am* 2011; 93(4): 341–347.
21. Abril JC, Montero M, Fraga M, et al. Ellipsoidal process of the femoral head in Legg-Calve-Perthes disease: effect of prophylactic hemiepiphysiodesis. *Indian J Orthop* 2022; 56(8): 1431–1438.
22. Aruwajoye OO, Monte F, Kim A, et al. A comparison of transphyseal neck-head tunneling and multiple epiphyseal drilling on femoral head healing following ischemic osteonecrosis: an experimental investigation in immature pigs. *J Pediatr Orthop* 2020; 40(4): 168–175.