2019

Natural history of the dysplastic hip following modern periacetabular osteotomy

Cody C. Wyles
Mayo Clinic

Juan S. Vargas
Mayo Clinic

Mark J. Heidenreich
Mayo Clinic

Kristin C. Mara
Mayo Clinic

Christopher L. Peters
University of Utah

See next page for additional authors

Natural History of the Dysplastic Hip Following Modern Periacetabular Osteotomy

Cody C. Wyles, MD, Juan S. Vargas, MD, Mark J. Heidenreich, MD, Kristin C. Mara, MS, Christopher L. Peters, MD, John C. Clohisy, MD, Robert T. Trousdale, MD, and Rafael J. Sierra, MD

Investigation performed at the Mayo Clinic, Rochester, Minnesota; Washington University in St. Louis, St. Louis, Missouri; and University of Utah, Salt Lake City, Utah

Background: Periacetabular osteotomy (PAO) is the most common treatment for symptomatic acetabular dysplasia, or developmental dysplasia of the hip (DDH), in skeletally mature patients. The purpose of this multicenter cohort study was to delineate the long-term radiographic natural history of the dysplastic hip following PAO.

Methods: We evaluated all patients undergoing PAO from 1996 to 2012 at 3 academic institutions in the United States. Inclusion criteria were PAO for DDH with a minimum 5-year radiographic follow-up. Exclusion criteria were PAO for isolated acetabular retroversion, neurogenic dysplasia, Legg-Calvé-Perthes disease, and prior hip surgery including osteotomies and arthroscopy. There were 288 patients, 83% of whom were women; the mean age and body mass index (BMI) were 29 years and 25 kg/m^2, respectively. The mean clinical and radiographic follow-up was 9.2 years (range, 5.0 to 21.1 years). Every preoperative and postoperative hip radiograph was assessed to determine the degree of osteoarthritis according to the Tönnis classification. Survivorship was analyzed by multistate modeling, enabling assessment of progression through the Tönnis grades rather than just individual transitions as with Kaplan-Meier techniques.

Results: At the time of final follow-up, 144 patients (50%) had progressed at least 1 Tönnis grade, with 42 patients (14.6%) undergoing total hip arthroplasty. The mean number of years spent in each Tönnis grade following PAO was 19 for Tönnis grade 1, 8 for Tönnis grade 2, and 4 for Tönnis grade 3. The probability of progression to total hip arthroplasty increased significantly on the basis of a higher initial Tönnis grade ($p < 0.001$). The most marked difference occurred between Tönnis grade 0 or 1 and Tönnis grade 2; for Tönnis grade 1, the probability of progression to total hip arthroplasty at 5 and 10 years was 2% and 11%, respectively, compared with 23% and 53%, respectively, for Tönnis grade 2.

Conclusions: PAO effectively alters the natural history of DDH. Precise radiographic progression based on the Tönnis grade can now be used to ascribe prognosis for the native hip. Importantly, this investigation demonstrates a stark increase in progression to total hip arthroplasty within 10 years of PAO for patients with preoperative Tönnis grade-2 osteoarthritis compared with those with Tönnis grade-0 or 1 osteoarthritis.

Level of Evidence: Therapeutic Level IV. See Instructions for Authors for a complete description of levels of evidence.

Periacetabular osteotomy (PAO) remains the most common treatment for symptomatic acetabular dysplasia of the hip (DDH) in skeletally mature patients with preserved articular cartilage[1]. Ganz et al.[1] developed the PAO in the mid-1980s, and the originating institution in Bern, Switzerland, recently published an impressive 30-year follow-up of the first 63 patients (75 hips)[2,3]. Other centers have reported shorter-term outcomes, but none have achieved follow-up of ≥20 years[4-9]. Although these studies provide valuable insight for prognosis, PAO surgery has undergone substantial technical maturation since its inception, while also becoming more reproducible. Perhaps most important in this developmental process was refinement of acetabular fragment positioning in the middle to late 1990s[10]. During that time, the importance of appropriate acetabular version became increasingly recognized. Many procedures during the early years lacked sufficient anteversion, creating iatrogenic femoroacetabular impingement[10,11]. The original technical description called for correcting the following: (1) lateral coverage of the femoral head, (2) medialization of the femoral head center of rotation, and (3) anterior-posterior femoral

Disclosure: The authors indicated that no external funding was received for any aspect of this work. On the **Disclosure of Potential Conflicts of Interest** forms, *which are provided with the online version of the article*, one or more of the authors checked "yes" to indicate that the author had a relevant financial relationship in the biomedical arena outside the submitted work (http://links.lww.com/JBJS/F207).

TABLE I Patient Characteristics of Cohort

Patient Factor*	Overall (N = 288)
Age† *(yr)*	29.2 ± 11.1 (11-50)
Females *(no. [%])*	238 (82.6)
BMI† *(kg/m²)*	25.4 ± 4.4
Preop. findings	
Tönnis grade *(no. [%])*	
0	150 (52.1)
1	115 (39.9)
2	21 (7.3)
3	2 (0.7)
Joint space† *(mm)*	5.3 ± 3.0
LCEA† *(deg)*	6.9 ± 10.4
Tönnis angle† *(deg)*	22.1 ± 7.1
ACE† *(deg)*	4.6 ± 14.4
Retroversion *(no. [%])*	72 (25.0)
Postop. findings	
Tönnis grade§ *(no. [%])*	
0	71 (24.7)
1	130 (45.1)
2	36 (12.5)
3	9 (3.1)
Total hip arthroplasty *(no. [%])*	42 (14.6)
Joint space† *(mm)*	4.3 ± 1.7
LCEA† *(deg)*	27.4 ± 10.6
Tönnis angle† *(deg])*	6.7 ± 8.1
ACE† *(deg)*	30.6 ± 13.4
Retroversion *(no. [%])*	43 (14.9)

*BMI = body mass index, LCEA = lateral center-edge angle, and ACE = anterior center-edge angle. †The values are given as the mean and the standard deviation, with the range in parentheses. ‡The values are given as the mean and the standard deviation. §Tönnis grade at the time of final follow-up.

head coverage. Contemporary correction maneuvers emphasize the critical step of version assessment and appropriate adjustment prior to accepting final fragment positioning. While technically more challenging, avoidance of acetabular retroversion further minimizes the risk of joint degeneration. Hence, osteotomies performed prior to this advancement in technique should be considered separately from those done after.

Although PAOs are believed to positively alter the natural history of DDH, there is a paucity of literature documenting the radiographic progression of osteoarthritis over time, especially in comparison with DDH managed nonoperatively. Generally, among reports that have attempted to characterize disease progression, the majority lack acknowledgment of the aforementioned technique changes, potentially undermining the study conclusions. Further, numerous studies have focused on progression to total hip arthroplasty as the primary end point[2,3,5,8,9,11]. Recently, more granular analyses have evaluated whether patients progressed to advanced stages of hip joint degeneration as measured by the Tönnis classification[2,5,9]. However, these studies lacked detail on the rate of progression between Tönnis stages, and the influence that patient and surgical factors can have on this rate. Lastly, existing literature lacks a control group of patients with DDH who were nonoperatively managed. A major step toward overcoming this barrier was recently taken with what we believe is the first report in which the long-term natural history of the dysplastic hip compared with hips of normal morphology was documented with a mean of 20 years and maximum of 35 years of follow-up[12]. Prior to this contribution, there was no means to leverage a historical control for evaluating the impact of PAO. A specific advantage from this study included implementation of statistical techniques with multistate modeling to delineate the precise radiographic progression of osteoarthritis in patients with DDH. Information from multistate modeling affords a greater level of detail than traditional Kaplan-Meier methodology, but requires an intensive effort as the model becomes more robust with the addition of every available radiograph[13].

The purpose of the present multicenter cohort study was to delineate the long-term radiographic natural history of the dysplastic hip following PAO. We evaluated a modern cohort after the advent of consistent version correction, leveraged multistate modeling techniques with grading of every available patient radiograph, and provided the first comparison with a historical control through the recent report on nonoperatively managed DDH[12] using the same statistical approach.

Materials and Methods

Following local institutional review board approval at each participating site, we evaluated all patients undergoing PAO, from 1996 to 2012, at 3 academic institutions including the

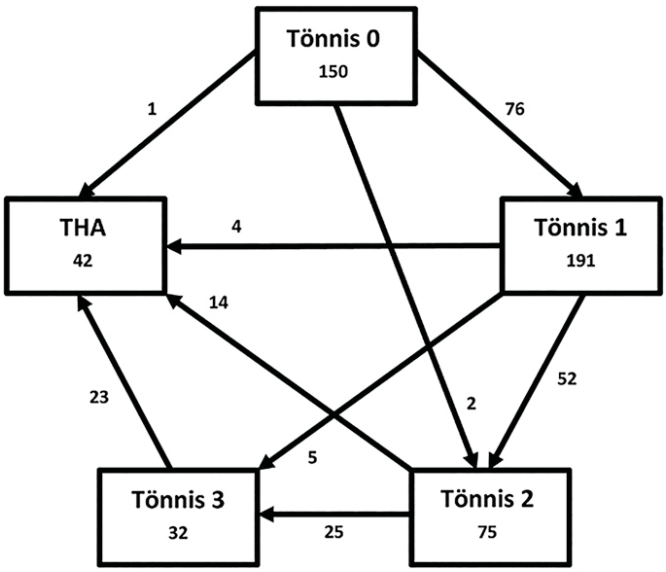

Fig. 1
The Tönnis grade of all 288 patients in the study. Transitions to various Tönnis grades or total hip arthroplasty (THA) at the time of final follow-up are shown with arrows.

TABLE II Mean Years Spent in Each Tönnis Grade by Hip Morphology and Surgical Intervention

Hip Morphology According to Tönnis Grade	Mean Years (95% CI)
DDH with PAO	
1	19 (15-24)
2	8 (6-11)
3	4 (3-5)
DDH with no PAO*	
1	12 (8-18)
2	6 (4-10)
3	2 (1-3)
Normal morphology with no PAO*	
1	18 (10-31)
2	9 (4-20)
3	0 (0-1)

*Historical data are from patients with contralateral total hip arthroplasty[12].

Mayo Clinic (Rochester, Minnesota), Washington University (St. Louis, Missouri), and the University of Utah (Salt Lake City, Utah). Inclusion criteria were PAO for DDH or for DDH and concomitant acetabular retroversion with a minimum 5-year radiographic follow-up. Exclusion criteria were PAO for isolated acetabular retroversion, neurogenic dysplasia, Legg-Calvé-Perthes disease, and any prior surgery about the hip including arthroscopy and childhood osteotomies. There were 288 patients in the final cohort, with 139 from the Mayo Clinic, 119 from Washington University, and 30 from the University of Utah. Overall, 83% of the patients were women, the mean age was 29 years, and the mean body mass index (BMI) was 25 kg/m^2 (Table I). The mean clinical and radiographic follow-up was 9.2 years (range, 5.0 to 21.1 years). Concomitant procedures at the time of PAO were performed in 137 patients and included 88 osteochondroplasties, 31 labral debridements, 19 labral repairs, 11 femoral osteotomies, and 1 trochanteric advancement. Additional procedures were performed following PAO in 46 patients and included 38 hardware removals, 6 arthroscopic explorations, 4 irrigation and debridements, 3 labral repairs, 1 hematoma evacuation, and 1 psoas tendon release.

Every available preoperative and postoperative anteroposterior radiograph of the pelvis or hip was independently assessed by 2 reviewers to determine the degree of osteoarthritis according to the Tönnis classification (grade 0 to 3). When the reviewers assessed for Tönnis grades on radiographs, patients were assigned to the highest grade possible on the basis of previously described criteria for the classification system. The following criteria were applied by the assessors: Tönnis grade 0 indicated the absence of degenerative changes; Tönnis grade 1 (mild), mild joint-space narrowing, mild sclerosis evidenced by widening of the sclerotic zone, and small marginal osteophytes; Tönnis grade 2 (moderate), moderate joint-space narrowing, moderate sclerosis of the femoral head or acetabulum, presence of small subchondral cysts within the femoral head or acetabulum, and moderate loss of femoral head sphericity; and Tönnis grade 3 (severe), severe joint-space narrowing (<1 mm) or obliteration of the joint space, evidence of large subchondral cysts on the femoral head or acetabulum, severe loss of sphericity of the femoral head, and advanced osteonecrosis. Evaluation of every radiograph was essential to enable survivorship analysis by multistate modeling. This method incorporates all individual radiographic data points for definition of disease progression with enhanced precision compared with Kaplan-Meier techniques. A total of 2,024 radiographs of the 288 patients were included in the analysis, with a median of 7 radiographs (range, 2 to 17 radiographs) per patient. In addition to Tönnis grade evaluation, anteroposterior pelvic and anteroposterior and lateral radiographs of the hip were assessed both preoperatively and postoperatively to determine the following parameters as previously described: minimum joint space in millimeters, lateral center-edge angle (LCEA), Tönnis angle, anterior center-edge angle (ACE), and acetabular retroversion (Table I)[14]. Progression of disease as determined by multistate modeling was compared with a historical control cohort of patients who either had DDH and did not undergo hip preservation surgery or had a hip with normal morphology as defined by an LCEA between 25° and 40° and a Tönnis angle of 0° to 10°[12]. These historical controls were evaluated by the same statistical techniques and were followed for up to 35 years.

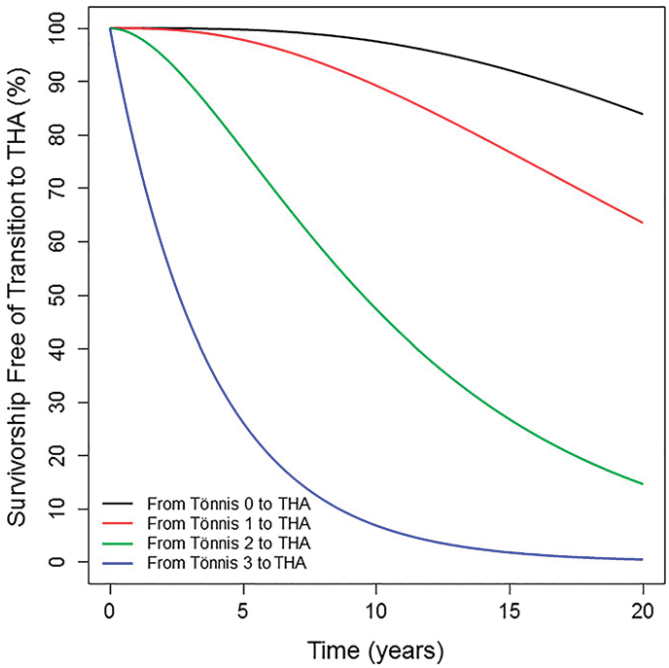

Fig. 2

Multistate modeling analysis demonstrating survivorship free of total hip arthroplasty (THA) based on the Tönnis grade at any given point in time. Thus, the moment a patient transitions to a more advanced Tönnis grade, they assume the natural history ascribed by the indicated curve, beginning at time zero.

Statistical Methods

Data were reported with means and ranges or counts and percentages for continuous and categorical variables, respectively, and using 95% confidence intervals (CIs) where appropriate. Cox proportional hazards regression models were used to evaluate progression from the baseline Tönnis grade to more advanced stages or total hip arthroplasty. Multistate Markov models were constructed using every available anteroposterior radiograph for every patient in the study[13] (Fig. 1). These models provide transition probability estimates between the Tönnis grades or eventual total hip arthroplasty. Furthermore, the multistate models evaluate the mean amount of time spent in each Tönnis grade. All analysis was conducted using R (version 3.1.1; R Foundation for Statistical Computing) and SAS (version 9.4; SAS Institute).

Results

At the time of final follow-up, 144 patients (50%) had progression of least 1 Tönnis grade, with 42 patients (14.6%) undergoing total hip arthroplasty (Fig. 1). The mean number of years spent in each Tönnis grade following PAO closely approximated a historical cohort with normal hip morphology[12]. However, patients with unmanaged DDH from the historical cohort had more rapid progression than patients who had normal morphology and patients from the current study who underwent PAO (Table II). The mean number of years spent in each Tönnis grade by morphology and/or surgical intervention was 19 years in Tönnis grade 1, 8 years in Tönnis grade 2, and 4 years in Tönnis grade 3 for patients with DDH who had PAO; 12, 6, and 2 years, respectively, for patients with DDH and no PAO; and 18, 9, and 0 years, respectively, for patients with normal morphology and no PAO (Table II).

The probability of progression to total hip arthroplasty increased significantly on the basis of a higher Tönnis grade at the time of PAO ($p < 0.001$) (Fig. 2). The most marked difference in natural history occurred between patients who had Tönnis grade 0 or 1 and those who had Tönnis grade 2 at the time of PAO. For patients with Tönnis grade 1, the probability of progression to total hip arthroplasty at 5 and 10 years was 2% and 11%, respectively, compared with 23% and 53% for patients with Tönnis grade 2 ($p < 0.001$) (Table III). Following PAO, the rate and pattern of progression approximated those for patients with normal morphology from the historical cohort but were significantly improved compared with patients with unmanaged DDH ($p < 0.05$ for all comparisons) (Table III).

TABLE III Probability of Transition to Subsequent Tönnis Grades or Total Hip Arthroplasty Based on Current Tönnis Grade

Hip Morphology According to Tönnis Grade and Surgical Intervention in Patients Followed for 5 and 10 Years	Probability of Transition According to Tönnis Grade				
	0	1	2	3	THA
Patients with DDH and a PAO					
5 years					
0	64%	32%	4%	1%	0.3%
1	–	77%	17%	4%	2%
2	–	–	53%	24%	23%
3	–	–	–	26%	74%
10 years					
0	40%	45%	10%	3%	3%
1	–	59%	22%	8%	11%
2	–	–	28%	19%	53%
3	–	–	–	7%	93%
Patients with DDH and no PAO at 10 years*					
0	56%	29%	9%	2%	5%
1	–	44%	25%	6%	25%
2	–	–	19%	7%	74%
3	–	–	–	0%	100%
Patients with normal morphology and no PAO at 10 years*					
0	65%	26%	6%	0%	3%
1	–	57%	24%	1%	18%
2	–	–	31%	1%	68%
3	–	–	–	0%	100%

*Historical data from patients with total hip arthroplasty on contralateral side[12].

TABLE IV Cox Proportional Hazards Regression Models Assessing Influence of Patient Demographics on Progression to More Advanced Tönnis Grades Following PAO*

	Tönnis Grade 0 to 1		Tönnis Grade 0 to 2		Tönnis Grade 0 to 3		Tönnis Grade 0 to THA	
Patient Factor	HR (95% CI)	P Value	HR (95% CI)	P Value	HR (95% CI)	P Value	HR (95% CI)	P Value
Male sex	0.86 (0.47-1.58)	0.63	1.89 (0.43-8.35)	0.40	0.81 (0.16-4.07)	0.80	0.86 (0.17-4.28)	0.85
Age, per decade	1.26 (1.03-1.53)	0.02	1.20 (0.81-1.78)	0.37	1.24 (0.70-2.21)	0.47	1.23 (0.69-2.20)	0.48
BMI, per kg/m^2	1.04 (0.99-1.10)	0.13	1.04 (0.93-1.16)	0.48	1.02 (0.87-1.18)	0.83	1.01 (0.87-1.18)	0.86

*Data were assessed for 150 patients (52%) who were classified as having Tönnis grade 0 at the time of PAO. PAO = periacetabular osteotomy, THA = total hip arthroplasty, HR = hazard ratio, CI = confidence interval, and BMI = body mass index.

The 10-year probability of patients with Tönnis grade 1 or 2 progressing to total hip arthroplasty according to morphology and/or surgical intervention was 11% for patients with Tönnis grade 1 and 53% for those with Tönnis grade 2 in the group who had DDH with PAO; 25% and 74%, respectively, in the group with DDH without PAO; and 18% and 68% in the group with normal morphology without PAO (Table III). Cox proportional hazards regression models demonstrated no significant overall relationship of age, sex, or BMI with progression to more advanced Tönnis stages following PAO (Table IV).

Discussion

PAO has been a revolutionary advancement for surgical preservation of the dysplastic hip since the mid-1980s. The technique was improved in the 1990s following recognition of acetabular version as a critical plane of correction. There remains a paucity of literature documenting outcomes following modern PAOs, specifically regarding comparison of a detailed radiographic natural history against a control group. This study is the first, to our knowledge, to address all of these deficiencies and confirms the ability of PAO to drastically improve the prognosis for the dysplastic hip. Precise natural history has now been described on the basis of the current Tönnis grade of a hip following modern PAO, which can aid in patient selection and prognostication. Similar to previous reports, a stark difference was identified in outcomes between patients with a Tönnis grade of <2 and those with a Tönnis grade of ≥2 at the time of PAO. However, contrary to previous studies, patient demographic factors including age, sex, and BMI were not associated with the rate of disease progression.

Determining the impact on natural history is particularly important for hip preservation procedures, given the goal of maximizing the longevity of the native joint. However, studies aiming to document the prognosis of unmanaged dysplasia have historically been challenging as essentially all current measures of PAO efficacy lack a control group. Special circumstances are required to radiographically follow a dysplastic hip longitudinally for an extended period of time without intervention. A previous report by Murphy et al. provided a baseline regarding this important question; nevertheless, drawing comparative conclusions regarding patients with PAO was difficult, given cohort heterogeneity[15]. An imperfect, but more homogeneous, group was used recently to determine the long-term radiographic natural history of the dysplastic hip compared with hips with normal morphology for up to 35 years[12]. This consisted of patients with Tönnis grade-0 arthritic changes in the native hip under study at the time of total hip arthroplasty on the contralateral side. In that study and the present study, every subsequent radiograph was assessed to determine progression through the Tönnis stages over time, enabling use of multistate modeling techniques. This form of assessment holds distinct advantages over Kaplan-Meier analysis by integrating every available data point instead of the time to a binary outcome (i.e., total hip arthroplasty versus no total hip arthroplasty). Thus, determination of the time spent in individual states (i.e., Tönnis stages) can be achieved, with precise prediction of a change in state at a time point of interest (i.e., percentage chance that a patient with Tönnis grade 2 will undergo total hip arthroplasty within 10 years). Therefore, this recent report of DDH versus the natural history of normal morphology not only serves as the most robust current control group for assessment of PAOs but also highlights an improved methodology for assessing osteoarthritis progression. Incorporating these data with the findings in the present study provides the groundwork for prognostication—a traditionally elusive task in the field of joint preservation, yet a critical tool in the era of shared decision-making. For example, using Table III, a surgeon can take the current Tönnis grade of a patient (for either PAO or unmanaged DDH) and ascribe a prognosis for outcomes at 5 and 10 years into the future.

Previous investigations of both larger cohort studies[5] and those with longer follow-up than the current study[2,9] have documented worse outcomes following PAO for patients with higher Tönnis grades. Although these are landmark works, conclusions maintained some level of uncertainty secondary to the heterogeneity of the evaluated patient populations. These limitations include the evaluation of patients with previous surgery, patients with various DDH etiologies, and patients undergoing PAO before and after recognition of version as a critical plane of correction. The current study included only a modern cohort with classic dysplasia, uniformly long-term

radiographic follow-up, and no previous surgery. Furthermore, incorporation of results from multiple high-volume centers enhances generalizability. These methodological advantages not only reinforce the important relationship between Tönnis grade and PAO outcomes previously documented by other groups but also provide a more exact delineation at different stages of disease and subsequent time points (Fig. 2, Table III). Furthermore, this study shows that compared with historical controls, PAO shifts the natural history to a path that closely approximates that of patients with normal native hip morphology, underscoring the validity of the integrated mechanical concept of hip osteoarthritis popularized by Ganz et al.[16].

This study must be interpreted in light of important limitations. First and foremost, although this investigation is the first, to our knowledge, to incorporate a control group for PAOs, these controls are historical and a different population. The control group in this study was identified among a cohort who had a contralateral total hip arthroplasty. While these patients were all <55 years old at the inception of evaluation, they were nevertheless older than patients in the present study and may have had different levels of activity and demand on the native dysplastic hip[12]. Certainly, a directly comparable and contemporary control cohort of patients with unmanaged DDH would be ideal; however, the feasibility of establishing such a control with longitudinal follow-up is questionable[15]. Second, radiographs from each of the 3 participating centers were graded independently at that site by 2 reviewers. This may introduce some intersite bias; however, sensitivity analysis demonstrated consistent results across sites. Thus, it may also be viewed as a strength resulting in greater generalizability of the presented data. Third, this study focuses on the Tönnis classification as a means of prognostication. Indeed, there are other important clinical and morphological characteristics that likely impact survivorship following PAO, including the precision of acetabular reorientation, femoral morphology, and status of the cartilage and labrum not captured by radiographs. These parameters may be the focus of future investigation. Fourth, the presented work does not account for the precision of acetabular correction for each individual case. Indeed, there is only 1 true perfect correction for each patient and that position differs slightly for each patient. This study evaluates patients after a time point when hip preservation surgeons became cognizant of the importance of incorporating version correction during acetabular reorientation.

This study confirms the ability of PAO to effectively alter the natural history of the dysplastic hip. Precise radiographic progression based on the Tönnis grade at the time of PAO can now be used to ascribe prognosis for the native hip. Importantly, this investigation demonstrates a stark increase in the rate of progression to total hip arthroplasty within 10 years of PAO for patients with Tönnis grade 2 compared with Tönnis grade 0 or 1 at the time of acetabular correction. Future reports evaluating PAOs would benefit from the use of multistate modeling techniques to evaluate outcomes, enabling hip preservation surgeons to continue improving this mainstay of management for the dysplastic hip. ■

Cody C. Wyles, MD[1]
Juan S. Vargas, MD[1]
Mark J. Heidenreich, MD[1]
Kristin C. Mara, MS[1]
Christopher L. Peters, MD[2]
John C. Clohisy, MD[3]
Robert T. Trousdale, MD[1]
Rafael J. Sierra, MD[1]

[1]Department of Orthopedic Surgery (C.C.W., J.S.V., M.J.H., R.T.T., and R.J.S.) and Division of Biomedical Statistics and Informatics (K.C.M.), Mayo Clinic, Rochester, Minnesota

[2]Department of Orthopedic Surgery, University of Utah, Salt Lake City, Utah

[3]Department of Orthopedic Surgery, Washington University, St. Louis, Missouri

E-mail address for R.J. Sierra: Sierra.rafael@mayo.edu

ORCID iD for C.C. Wyles: 0000-0002-8629-7567
ORCID iD for J.S. Vargas: 0000-0002-0511-6382
ORCID iD for M.J. Heidenreich: 0000-0002-5196-8527
ORCID iD for K.C. Mara: 0000-0002-8783-0191
ORCID iD for C.L. Peters: 0000-0001-9608-3346
ORCID iD for J.C. Clohisy: 0000-0001-7040-616X
ORCID iD for R.T. Trousdale: 0000-0002-4572-7540
ORCID iD for R.J. Sierra: 0000-0002-8513-1477

References

1. Ganz R, Klaue K, Vinh TS, Mast JW. A new periacetabular osteotomy for the treatment of hip dysplasias. Technique and preliminary results. Clin Orthop Relat Res. 1988 Jul;232:26-36.

2. Lerch TD, Steppacher SD, Liechti EF, Tannast M, Siebenrock KA. One-third of hips after periacetabular osteotomy survive 30 years with good clinical results, no progression of arthritis, or conversion to THA. Clin Orthop Relat Res. 2017 Apr;475(4):1154-68.

3. Steppacher SD, Tannast M, Ganz R, Siebenrock KA. Mean 20-year followup of Bernese periacetabular osteotomy. Clin Orthop Relat Res. 2008 Jul;466(7):1633-44. Epub 2008 May 1.

4. Crockarell J Jr, Trousdale RT, Cabanela ME, Berry DJ. Early experience and results with the periacetabular osteotomy. The Mayo Clinic experience. Clin Orthop Relat Res. 1999 Jun;363:45-53.

5. Hartig-Andreasen C, Troelsen A, Thillemann TM, Søballe K. What factors predict failure 4 to 12 years after periacetabular osteotomy? Clin Orthop Relat Res. 2012 Nov;470(11):2978-87.

6. Matheney T, Kim YJ, Zurakowski D, Matero C, Millis M. Intermediate to long-term results following the Bernese periacetabular osteotomy and predictors of clinical outcome. J Bone Joint Surg Am. 2009 Sep;91(9):2113-23.

7. Sanchez-Sotelo J, Trousdale RT, Berry DJ, Cabanela ME. Surgical treatment of developmental dysplasia of the hip in adults: I. Nonarthroplasty options. J Am Acad Orthop Surg. 2002 Sep-Oct;10(5):321-33.

8. Trumble SJ, Mayo KA, Mast JW. The periacetabular osteotomy. Minimum 2 year followup in more than 100 hips. Clin Orthop Relat Res. 1999 Jun;363:54-63.

9. Wells J, Millis M, Kim YJ, Bulat E, Miller P, Matheney T. Survivorship of the Bernese periacetabular osteotomy: what factors are associated with long-term failure? Clin Orthop Relat Res. 2017 Feb;475(2):396-405. Epub 2016 May 12.

10. Trousdale RT, Cabanela ME. Lessons learned after more than 250 periacetabular osteotomies. Acta Orthop Scand. 2003 Apr;74(2):119-26.

11. Albers CE, Steppacher SD, Ganz R, Tannast M, Siebenrock KA. Impingement adversely affects 10-year survivorship after periacetabular osteotomy for DDH. Clin Orthop Relat Res. 2013 May;471(5):1602-14. Epub 2013 Jan 25.

12. Wyles CC, Heidenreich MJ, Jeng J, Larson DR, Trousdale RT, Sierra RJ. The John Charnley Award: redefining the natural history of osteoarthritis in patients with hip dysplasia and impingement. Clin Orthop Relat Res. 2017 Feb;475(2):336-50.

13. Meira-Machado L, de Uña-Alvarez J, Cadarso-Suárez C, Andersen PK. Multi-state models for the analysis of time-to-event data. Stat Methods Med Res. 2009 Apr;18(2):195-222. Epub 2008 Jun 18.

14. Clohisy JC, Carlisle JC, Beaulé PE, Kim YJ, Trousdale RT, Sierra RJ, Leunig M, Schoenecker PL, Millis MB. A systematic approach to the plain radiographic evaluation of the young adult hip. J Bone Joint Surg Am. 2008 Nov;90(Suppl 4):47-66.

15. Murphy SB, Ganz R, Müller ME. The prognosis in untreated dysplasia of the hip. A study of radiographic factors that predict the outcome. J Bone Joint Surg Am. 1995 Jul;77(7):985-9.

16. Ganz R, Leunig M, Leunig-Ganz K, Harris WH. The etiology of osteoarthritis of the hip: an integrated mechanical concept. Clin Orthop Relat Res. 2008 Feb;466(2):264-72. Epub 2008 Jan 10.