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Structured-mentorship Program for Periacetabular Osteotomy Resulted in Few Complications for a Low-volume Pelvic Surgeon

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Abstract

Background The Bernese periacetabular osteotomy (PAO) is a complex surgical procedure with a substantial learning curve. Although larger hospital and surgeon procedure volumes have recently been associated with a lower risk of complications, in geographically isolated regions, some complex operations such as PAO will inevitably be performed in low volume. A continuous structured program of distant mentoring may offer benefits when low numbers of PAOs are undertaken, but this has not been tested. We sought to examine a structured, distant-mentorship program of a low-volume surgeon in a geographically remote setting.

Questions/purposes The purposes of this study were (1) to identify the clinical results of PAO performed in a remote-mentorship program, as determined by patient-reported outcome measures and complications of the surgery; (2) to determine radiographic results, specifically postoperative angular corrections, hip congruity, and progression of osteoarthritis; and (3) to determine worst-case analysis of PAO survivorship, defined as nonconversion to THA, in a regionally isolated cohort of patients with a high rate of followup.

Methods Between August 1992 and August 2016, 85 PAOs were undertaken in 72 patients under a structured, distant-mentorship program. The patients were followed for a median of 5 years (range, 2-25 years). There were 18 males (21 hips) and 54 females (64 hips). The median age of the patients at the time of surgery was 26 years (range, 14-45 years). One patient was lost to followup (two PAOs) and one patient died as a result of an unrelated event. Patient-reported outcome measures and complications were collected through completion of patient and doctor questionnaires and clinical examination. Radiographic assessment of angular correction, joint congruity, and osteoarthritis was undertaken using standard radiology software. PAO survivorship was defined as nonconversion to THA and is presented using worst-case analysis. The loss-to-followup quotient—number of patients lost to followup divided by the number of a patients converted to THA—was calculated to determine quality of followup and reliability of survivorship data.

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Each author certifies that his or her institution approved the human protocol for this investigation and that all investigations were conducted in conformity with ethical principles of research.
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Results The median preoperative Harris hip scores of 58 (range, 20-96) improved postoperatively to 78 (range, 33-100), 86 (range, 44-100), 87 (range, 55-97), and 80 (range, 41-97) at 1, 5, 10, and 14 years, respectively. Sink Grade III complications at 12 months included four relating to the PAO and one relating to the concomitant femoral procedure. The median lateral center-edge angle correction achieved was 22° (range, 3°-50°) and the median correction of acetabular index was 19° (range, 3°-37°). Osteoarthritis progressed from a preoperative mean Tönnis grade of 0.6 (median, 1; range, 0-2) to a postoperative mean of 0.9 (median, 1; range, 0-3). Six hips underwent conversion to THA: five for progression of osteoarthritis and one for impingement. At 12-year followup, survivorship of PAO was 94% (95% confidence interval [CI], 85%-98%) and survivorship with worst-case analysis was 90% (95% CI, 79%-96%). The loss-to-followup quotient for this study was low, calculated to be 0.3.

Conclusions When PAO is performed using a structured process of mentoring under the guidance of an expert, one low-volume surgeon in a geographically isolated region achieved good patient-reported outcomes, a low incidence of complications at 12 months, satisfactory radiographic outcomes, and high survivorship. A structured distant-mentorship program may be a suitable method for initially learning and continuing to perform low-volume complex surgery in a geographically isolated region.

Level of Evidence Level IV, therapeutic study.

Introduction

The Bernese periacetabular osteotomy (PAO) is a complex but infrequently performed surgical procedure with a considerable learning curve previously defined to be in the range of a surgeon's first 20 or 30 osteotomies [23]. Although this procedure has been successful in treating hip dysplasia, it also can result in serious complications [3, 11]. Traditionally, fellowship programs have provided a method of learning complex surgical procedures. Local mentoring to learn complex surgery has been shown to be of benefit in general surgery [12, 16]. Previously we have reported early outcomes of PAO learned under a distant-mentorship program [22].

Since the 1970s, greater hospital and surgeon procedure volumes have been associated with lower rates of mortality and complications after surgical procedures [21, 35]. Whereas some authors have suggested that hospitals and surgeons performing high-volume orthopaedic procedures may indeed experience lower risks of complications, the association between procedure volume and patient outcome remains unclear and the magnitude of the association can vary greatly [1, 24, 37]. However, in a geographically isolated region, certain surgical procedures will inevitably have to be performed in low volume unless there is an acceptable mechanism for referral, which is often not available. One example is PAO to treat residual hip dysplasia in adolescents and young adults. The prevalence of isolated developmental dysplasia of the hip (DDH) in South Australia has been estimated to be 10.5 per 1000 births, mostly identified during the neonatal period [48]. The subsequent prevalence of adult hip dysplasia in such a region with a well-established neonatal hip screening program is likely to be very small, resulting in a relatively low number of patients with DDH undergoing PAO. Therefore, a structured distant-mentorship program was established with one surgeon at the major teaching hospital in South Australia. Continuation of this structured program of distant mentoring is likely to be beneficial when low-volume surgery is undertaken in a geographically isolated region.

The purposes of this study, therefore, were (1) to identify the clinical results of PAO, as determined by patient-reported outcome scores and complications of the surgery; (2) to determine radiographic results, specifically postoperative angular corrections, hip congruity, and progression of osteoarthritis; and (3) to determine worst-case analysis of PAO survivorship, defined as nonconversion to THA, in a geographically isolated cohort of patients with a high rate of followup.

Materials and Methods

Institutional review board approval was obtained for this retrospective study. Between August 1992 and August 2016, 85 PAOs were undertaken in 72 patients (18 males [21 hips]; 54 females [64 hips]) under a structured distant-mentorship program. This represents an average of approximately four PAOs annually (range, 0-11 per year). The median age of the cohort at surgery was 26 years (range, 14-45 years). Twelve patients underwent bilateral, staged PAO. Twelve of the 85 hips had a femoral osteotomy at the time of PAO or as a staged procedure. In all patients, the indication for surgery was symptomatic hip dysplasia with pain from the hip. Fifty-six (45 patients) of the 85 hips underwent standard PAO for classic uncomplicated primary hip dysplasia. The other 29 PAOs were undertaken in patients with an additional diagnosis such as Perthes disease (seven hips) and polio (one hip) or abnormal femoral anatomy, previous acetabular/proximal femoral surgery, or in patients who underwent a concomitant or staged femoral osteotomy. Severity of dysplasia was classified according to Severin on preoperative plain radiographs [36]. No hips were classified as Severin I, V, or VI. One hip was a Severin Grade II dysplasia, 16 hips Grade III, and 68 hips Grade IV dysplasia.

This mentorship program was set up specifically to allow a low-volume surgeon to perform PAO in a

geographically isolated region. The procedures were performed at the largest tertiary referral hospitals in the state with capacities up to 800 beds. The program also involved review of radiographs and clinical material for purposes of teaching the surgical protégé and use of a longitudinally maintained clinical database for recording and retrieval of patients' outcomes data. One surgeon (DWH) participated in this program, as the protégé, and this article presents his surgical results achieved under this program. This surgeon was a newly established consultant orthopaedic and trauma surgeon at the time of commencing the mentorship program but had not performed any PAO or any other pediatric or adult pelvic osteotomies before the learning phase. Three surgeons acted as mentors on this program; the chief mentor was the developer of the operation and the other two had performed many hundreds of PAOs before participating in the program.

The initial 26 PAOs during the learning phase of the mentorship were discussed with one of the three mentors both during preoperative planning and for the postoperative evaluation. Also during this period, the protégé attended two cadaver workshops and made annual visits to the mentor, which continued for the first 5 years but then was reduced to once every 3 to 4 years thereafter. The protégé attended international meetings with PAO surgeons biannually including the International Hip Society meeting, the Young Adult Hip Course in Berne, and the annual meeting of the American Academy of Orthopaedic Surgeons. Mentorship beyond the learning phase included additional regular visits to high-volume centers on different continents to observe surgery and review patient pathways and procedures. Attendance and active participation at international conferences to discuss PAO and joint-preservation surgery also formed part of the continued mentorship program. During the latter part of the mentorship program, all complex procedures and procedures in patients with severe dysplasia were discussed with the mentor, usually via email. Overall, approximately one in two PAOs were discussed with the mentor both pre- and postoperatively. Some adaptations to the technique were made. A double surgical approach was used for the first 11 PAOs [22], whereas all subsequent PAOs were performed through a single anterior Smith-Peterson approach [17]. Although no patients underwent prior arthroscopic labral surgery, an arthrotomy and femoral neck osteoplasty in addition to the PAO were performed almost routinely in later procedures (42 PAOs). Further adaptations, learned from visits to centers in America, included the use of intraoperative fluoroscopy to judge more accurately the site of the ischial osteotomy. Other adaptations included palpation from inside the pelvis to judge the depth of osteotomy, a change in order of the posterior column osteotomy, and the use of a pencil burr to join the ilium osteotomy to the posterior column osteotomy.

Through repeated discussions and the sharing of experiences under the mentorship program, it became apparent that radiographic assessment of dysplasia and the apparent correction achieved were influenced by the specific radiographic techniques used to measure these. This related to patient positioning, body habitus, x-ray beam centering and direction, pelvic distance and orientation from the x-ray source as well as other factors. Although the pelvis of most individuals tilts posteriorly on standing, which apparently increases acetabular anteversion and reduces anterior acetabular coverage, the degree of pelvic tilt is quite variable among patients with hip dysplasia. Furthermore, the acetabular position measured on intraoperative posteroanterior (PA) fluoroscopy images was noted to be different from the position on preoperative AP radiographs of the pelvis. PA fluoroscopy images centered on the pelvis cause an apparent increase in acetabular anteversion and reduction of anterior acetabular coverage compared with AP radiographs [25]. After visits to high-volume centers and under mentorship guidance, the initial protocol was adapted to incorporate both supine and standing pre- and postoperative AP radiographs. Intraoperatively, a combination of PA fluoroscopy images and AP pelvic radiographs was used to achieve a functional correction referenced to the standing AP pelvic radiograph.

All patients were reviewed clinically and radiographically preoperatively and, aside from two hips (1 patient) lost to followup, postoperatively at 3 months, 1 year, 2 years, 5 years, 10 years, and then at 2 to 3 yearly intervals thereafter. Patient-reported outcome measures, including Harris hip and Harris pain scores (HHS) [19], were collected through completion of patient and doctor questionnaires and clinical examination. All patients not identified here as lost to followup had HHS scores gathered both before and at latest followup. Complications within the first 12 months of surgery were graded according to the Sink modification of the Clavien-Dindo system [39]. A Sink Grade I complication results in no treatment, a Grade II complication results in deviation from the normal postoperative course, a Grade III complication is treatable but results in an intervention, a Grade IV complication is a life-threatening complication, and a Grade V complication is death. Survivorship of PAO was defined as nonconversion to THA. The latest clinical and radiographic followup, at a median of 5 years after PAO (range, 2-25 years), involved all but two patients, one who had bilateral PAOs and one who died 14 months postsurgery from an unrelated cause. The loss-to-followup quotient is an indicator of the reliability of calculated survivorship of a procedure [33] and, for PAO survival, can be calculated by dividing the number of PAOs lost to followup by the number of known conversions to THA. If the quotient is > 1, the calculated survival rate is likely to be unreliable. We calculated this quotient for our patient cohort. The high followup rate in this study allowed

us to perform worst-case analysis on PAO survivorship. All pre- and postoperative radiographs were independently reviewed by two of the authors (DTSC, DWH) to grade the degree of osteoarthritis according to the criteria of Tönnis [41] and assess joint congruency using the Yasunaga grading system [47]. Postoperative Tönnis grading was assessed on the latest radiographic followup or the last radiograph taken before conversion to THA, patient death, or loss to followup. Lateral center-edge angle (LCEA) of Wiberg [46] and acetabular index (AI) angle were measured by the same two authors on standard radiographic viewing software (Vue PACS; Carestream Health, Inc, New York, NY, USA).

Statistical analyses were performed using GraphPad Prism software, Version 4 (GraphPad Software, Inc, San Diego, CA, USA). PAO survivorship was determined using the Kaplan-Meier method with 95% confidence intervals (CIs) and included worst-case analysis assuming that PAOs lost to followup had undergone conversion to primary THA. Survivorship was reported at a maximum of 12 years after which time < 20 hips remained at risk of conversion to THA.

Results

The median HHS was 58 (range, 20-96) preoperatively and postoperatively improved to 78 (range, 33-100), 86 (range, 44-100), 87 (range, 55-97), and 80 (range, 41-97) at 1, 5, 10, and 14 years, respectively. The median Harris pain score was 20 (range, 0-44) preoperatively and postoperatively improved to 40 (range, 0-44), 40 (range, 10-44), 40 (range, 20-44), and 40 (range, 10-44) at 1, 5, 10, and 14 years, respectively. Forty-one PAOs had a postoperative complication within the first 12 months of surgery (Table 1) classified according to the Sink modification of the Clavien-Dindo complication system [39]. Five PAOs had a Sink Grade III complication in that they underwent further surgical intervention, four of which were related to the PAO and one to the concomitant femoral procedure. Those related to the PAO included one patient who underwent refixation for delayed union, one revision correction and fixation of PAO, one removal of an irritating anterosuperior iliac spine (ASIS) screw, and one wound infection treated with irrigation and débridement. The complication relating to the concomitant femoral procedure was refixation of a neck osteotomy. Grade II complications, resulting in a deviation from the normal clinical course, included one temporary femoral nerve palsy and one temporary partial sciatic nerve palsy in association with a posterior column fracture. Both of these nerve injuries fully recovered within 3 months. There were eight isolated posterior column fractures that united uneventfully, two ischial nonunions causing painful pubic stress fractures that eventually settled, and three superficial wound infections treated using antibiotics. Twelve of the 41 complications within the first 12 months after surgery occurred in the first 26 PAOs performed during the learning phase. Beyond the initial 12-month followup period, seven hips underwent reoperation as a result of complications related to the PAO. The reoperations included two surgical hip dislocations with neck ostectomy and labral repair, two removals of ASIS screws, one excision of HO and removal of an ASIS screw, one revision PAO and femoral varus osteotomy, and one hip arthroscopy and labral débridement.

In comparison to the preoperative radiographic values, there was an overall increase in the LCEA and a decrease in the AI after PAO. The preoperative median LCEA of 6° (range, -20° to 23°) was corrected to a postoperative median LCEA of 30° (range, 11°-52°) equating to a median correction of 22° (range, 3°-50°) (Table 2). The median preoperative AI of 25° (range, 11°-45°) was corrected to a postoperative median AI of 6° (range, -13° to 18°) equating to a median correction of 19° (range, 3°-37°) (Table 2). Hip congruency after PAO improved by one Yasunaga grade in 18 hips and deteriorated by one Yasunaga grade in two hips. No hips, either pre- or postoperatively, were assessed

Table 1. Number and severity of complications within the first 12 months after PAO according to the Sink modification of the Clavien-Dindo classification system

Sink grading	Level of complication	Number of PAOs
0	No complication	44
I	Complication requiring no treatment	25
II	Complication requiring deviation from normal clinical course	11
III	Complication requiring surgical intervention	5
IV	Life-threatening complication	0
V	Death	0

PAO = periacetabular osteotomy.

Table 2. Comparison of surgical volume and radiographic correction achieved

Study	Total number of PAOs reported	Approximate average number of PAOs performed per year	Mean LCEA correction achieved*	Mean AI correction achieved*
This study	85	4	23° (median 22°; range, 3°-50°)	19° (median 19°; range, 3°-37°)
Biedermann et al. [3]	60	7	23°	5°
Crockarell et al. [13]	21	9	22°	13°
Matta et al. [30]	66	9	28°	22°
Clohisy et al. [8]	16	11	45°	26°
Clohisy et al. [10]	24	13	28°	17°
Siebenrock et al. [38]	75	21	28	20
Mayo et al. [31]	225	23	24°	18°
Trumble et al. [43]	225	23	23°	17°
Cunningham et al. [14]	207	69	27°	18°

*Values have been rounded to the nearest degree; PAOs = periacetabular osteotomies; LCEA = lateral center-edge angle; AI = acetabular index.

as having Yasunaga Grade A, excellent congruity. Postoperatively, 48 hips were graded as good, 33 as fair, and four as poor compared with, respectively, 32, 48, and five hips preoperatively. Pre- and postoperative grading of osteoarthritis was performed using the Tönnis classification system (Table 3). Of the 85 hips, osteoarthritis progressed from a preoperative mean Tönnis grade of 0.6 (median, 1; range, 0-2) to a postoperative mean of 0.9 (median, 1; range, 0-3). At latest radiographic review, 19 hips progressed one Tönnis grade and two hips progressed three Tönnis grades relative to the preoperative grade. Of the 21 hips that showed progression of osteoarthritis, eight had a preoperative Tönnis grade of 0, seven had a preoperative Tönnis grade of 1, and six had a preoperative Tönnis grade of 2.

Six of the 85 PAOs have undergone conversion to THA. Of these, five were performed at our institution as a result of hip pain and progression of hip osteoarthritis and one was undertaken elsewhere for impingement. Time from PAO to THA was 15, 34, 36, 41, 146, and 168 months. Four of the six patients were aged ≥ 30 years at the time of PAO and three of the six patients had preoperative Tönnis Grade 2 osteoarthritis. At 12-year followup, survivorship of PAO was 94% (95% CI, 85%-98%) (Fig. 1). One patient died of an unrelated cause 14 months after surgery and one patient with bilateral PAOs was lost to followup at 5 years. PAO survivorship by worst-case analysis was 90% (95% CI, 79%-96%) at 12 years. A method of assessing the reliability of survivorship analysis for arthroplasty has been described as a loss-to-followup quotient [33]. With two PAOs lost to followup, our loss-to-followup quotient was calculated to be 0.3, suggesting a reliable survivorship data set [33].

Discussion

There is an increasing body of evidence suggesting that better surgical results and fewer complications are achieved with increased specialization and higher volumes [2, 5, 28]. As a consequence, centralization of surgical services such as for polytrauma management and cancer treatment has been successfully developed in many countries [4]. However, high-quality evidence in complex orthopaedic procedures like PAO is lacking. The volume of surgery performed at a unit may in fact be an imperfect surrogate for other variables, which may contribute more to patient outcomes. Furthermore, service centralization may not be practical for infrequently performed complex surgical procedures such as PAO in a country with a sparse population covering a large geographic area. The best method of training a surgeon to perform this complex procedure is

Table 3. Pre- and postoperative classification of hip osteoarthritis according to the Tönnis grading system

Tönnis grade	Degree of osteoarthritis	Number of hips preoperatively	Number of hips postoperatively
0	None	40	32
1	Mild	36	35
2	Moderate	9	10
3	Severe	0	8

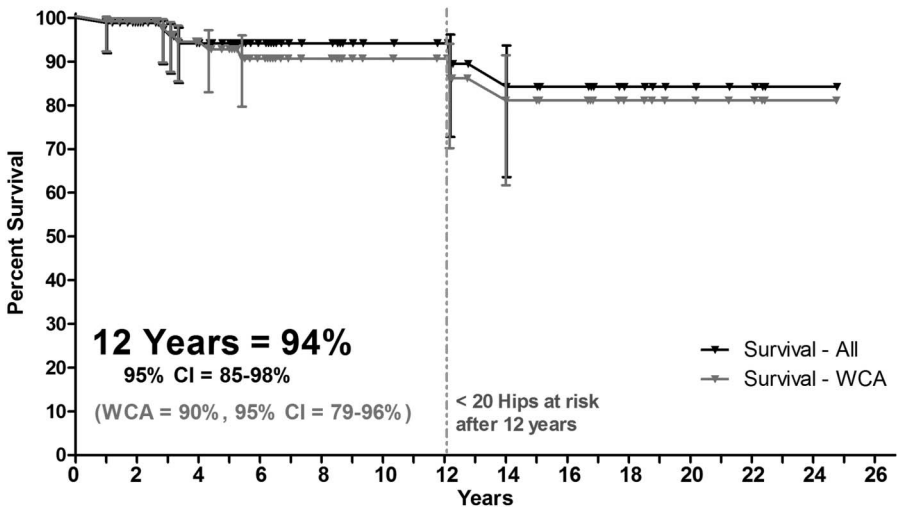

Fig. 1 Graph showing percent survivorship against years after PAO with conversion to THA defined as the endpoint. Graph also shows survivorship with worst-case analysis (WCA) assuming that any PAO lost to followup had undergone conversion to THA.

yet to be determined. Although distant mentorship may be a potential method of learning PAO, Novais et al. [34] have shown that two young surgeons initially trained within a formal structured hip preservation fellowship can perform PAO with a relatively low risk of complications. However, after this initial period, surgeons in a geographically isolated region are likely to perform PAO infrequently. Distant mentorship during this latter period is likely to maintain surgical expertise and good patient outcomes. Furthermore, such a structured program of mentorship can allow the surgeon to make subtle adaptations to the surgery to optimize his or her surgical technique. The clinical and radiographic results presented here show that one surgeon was able to perform PAO in a geographically isolated center under the guidance of a structured mentorship program and achieve high hip scores, few complications, and good reconstructive durability.

This study has a number of limitations. The outcomes of the PAO may have been influenced by a number of factors that have not been taken into account in this study. First, the results represent a single protégé's experience in a mentorship program; external validity (generalizability) must therefore be considered as this structured-mentorship approach is considered for wider adoption. Overall outcomes may have been influenced by the level of experience of the surgeon at the time of surgery given that the PAOs involved in the study were undertaken by the senior author (DWH) both during his initial learning curve as well as during subsequent years during which substantial experience had been gained. The surgical technique, available technologies, and perioperative management also evolved over this period from 1992 to 2016. There was also substantial variation among the PAOs in the complexity of dysplasia, underlying diagnosis, and previous hip surgery. Whereas the reported outcomes of PAO are good in this study, it is difficult to conclusively interpret the contribution of a distant-mentorship program on these results, because no direct comparison can be made to a control group in the form of a low-volume PAO center without a structured-mentorship program.

Moreover, our outcomes cannot be comprehensively or directly compared with other centers because there are many other factors beyond clinical, radiologic, and survivorship outcomes that can and have been used to evaluate outcomes of PAO. In addition, we have not presented surgical-time data, which have been considered to be a possible surrogate measure for surgical performance and learning curve [34]. However, surgical time is likely to be an outcome affected by multiple factors such as complexity of the procedure and the experience of the entire surgical team. Qualitative and quantitative radiographic assessment of the hips was performed by two surgeons using standard clinical radiographic-viewing software. Many of the standard radiographic measurements used to diagnose DDH have been shown not to be reliable or reproducible [6, 9]. Assessment of parameters such as hip congruency has been shown to have low intraobserver and interobserver reliability [26]. Although we have no κ values for this study, we present comparative data and feel that the change in value over a series of radiographs in the same patient is more valuable than a single absolute radiographic reading. Finally, use of conversion to THA as a study endpoint to denote an unsuccessful reconstruction is limited by the fact that not all patients in these remote areas may have easily been able to return for repeat reconstruction; however, the generally high HHS suggests that the patients who did not

undergo conversion to THA usually achieved a high degree of pain relief and functional restoration.

Patient-reported outcomes at a minimum of 2 years, from a large multicenter cohort of PAOs, showed a mean improvement in the modified HHS of 23.6 points (95% CI, 21.5-25.5) [7]. The HHS improvement in our study was similar, namely 22 points at 1 year and 30 points at 5 years. Complications of PAO have previously been reported in a nonstandardized manner, making it difficult to compare the complication profile of different patient cohorts. In 2012, Sink et al. [39] reviewed and adapted the general surgical Clavien-Dindo classification system for use with hip-preservation surgery. A multicenter study of PAOs used this classification to examine complication severity from seven high-volume North American centers. Complications were reported in 71 of 205 (35%) PAOs 1 year after surgery. Fifty-nine patients (29%) had Sink Grade I or II complications, and 12 (6%) had Grade III or IV complications [49]. The complications in the current study at 12-month followup are similar to those of the high-volume centers with only five (6%) Grade III or IV complications being identified. Of the PAOs performed during the learning phase of the mentorship program (first 26 PAOs), none had a Sink Grade III or IV complication at 12 months. Similar to Novais et al. [34], our study suggests that the risk of a Grade III or IV complication did not decrease with increasing surgeon experience. The reoperation rate beyond the 12-month postoperative period was not dissimilar to many other published series [11, 49].

In this study, there were eight posterior column fractures and two symptomatic ischial nonunions. Posterior column complications have been variably described with up to 14% reported in early series [13, 49]. The bone between the ilium osteotomy and posterior column, along the ilioischial line, is often very sclerotic and of variable thickness and orientation, rendering it prone to fracture. Although these complications are still reported, it is likely that many fractures are not initially recognized or reported but subsequently identified on three-dimensional imaging [34]. This may contribute to the reported prevalence of pubic nonunions (5%-14%) and pubic stress fractures (2%-18%) [27, 42]. Through guidance from the mentorship program, the surgeon adapted his technique by changing the order of osteotomies performed using a high-speed pencil burr across the ilioischial line and using intraoperative fluoroscopy when performing the osteotomy in the posterior column. Furthermore, finger palpation is used in an attempt to reduce posterior column fractures at the inferior ischial osteotomy site. These are both examples of operative technique adaptations made by the surgeon after visits and discussions with various experts throughout the mentorship program.

A LCEA between 30° and 40° has been considered to improve hip durability after PAO [20]. The median postoperative LCEA in this study was 30°, which is similar to that of high-volume centers (Table 2) [8, 10, 14, 30, 31, 43]. Crockerall et al., who report performing more than twice as many PAOs as this study, achieved a postoperative mean LCEA of 24° (range, 11°-45°) and a mean AI of 11° (range, 0°-27°) in a series of their first 21 hips [13]. Siebenrock et al., who report performing > 20 PAOs per year, achieve a mean postoperative LCEA of 34° (range, 10°-55°) and a mean postoperative AI of 6° (range, -15° to 18°) [38]. A lack of hip congruence is also considered to be a predictive factor for conversion to THA after PAO [20]. In this study, congruency of the hip was improved by one Yasunaga grade in 18 PAOs, whereas only two hips had worse congruency on immediate postoperative radiographs. Of the two hips showing a reduction in hip congruency, both had further progression of Tönnis grade and one underwent conversion to THA at 41 months post-PAO. Although some PAO studies have noted conversion to THA in hips with advanced preoperative osteoarthritis, there are few reliable radiographic factors that can predict a successful PAO outcome [32]. Analyzing the Tönnis grade progression of osteoarthritis in this study has not demonstrated any trends to suggest the likelihood of PAO conversion to THA.

Survivorship of PAO was defined in this study as nonconversion to THA. Results from a high-volume center in North America showed a PAO survivorship of 92% at 15 years after PAO for DDH. Eight of 238 hips underwent THA at a mean of 6.8 years, whereas 22 hips were lost to followup [45]. Hartig-Andreasen et al. report having performed 451 PAOs in just under 9 years (average of 69 PAOs per year). Their overall survivorship at 12.4 years was 75% (95% CI, 68%–80%) after the exclusion of 50 hips resulting from loss to followup [20]. Other high-volume studies have reported a survivorship range between 75% and 93% over 10 years with varying numbers lost to followup [15, 18, 20, 29, 40, 44]. Survivorship at 12 years in the current study group was 94% (95% CI, 85%-98%). Analysis of survivorship without taking loss to followup into consideration can provide an overoptimistic picture of the results. Therefore, consideration of the loss-to-followup quotient assigned to the survivorship calculation can provide an indication of the reliability of the latter. In our study, when loss to followup was taken into account through worst-case analysis, survivorship at 12 years was 90% (95% CI, 79%-96%). Worst-case analysis of survivorship in this study was similar to that of high-volume centers and, importantly, the quotient suggested high reliability of these results given the low number of losses to followup. A high number of losses to followup compared with the number of conversions to THA results in a high loss to followup quotient and less reliable survivorship outcome data (Table 4).

In conclusion, when PAO was performed using a structured process of mentoring under the guidance of an

Table 4. Comparison of surgical volume, number of PAOs converted to THA/hip fusion, and number of hips lost to followup

Study	Total number of PAOs (approximate average per year)	PAO conversion to THA/fusion	Number of hips lost to followup	Mean followup and (range) in years	Loss-to-followup quotient
This study	85 (4)	6	2	8 (median 5; range, 2-25)	0.3
Steppacher et al. [40]	75 (21)	27	7	20.4 (range, 19-23)	0.25
Siebenrock et al. [38]	75 (21)	12	4	11.3 (range, 10–13.8)	0.3
Grammatopoulos et al. [18]	68 (5)	4	2	8 (range, 2-17)	0.5
Hartig- Andreasen et al. [20]	316 (54)	69	50	8 (range, 4-12)	0.72
Wells et al. [44]	189 (26)	26	37	18 (range, 14-22)	1.42
Wells et al. [45]	238 (17)	8	22	10.3	2.75

PAO = periacetabular osteotomy.

expert, a low-volume surgeon in a geographically isolated region could achieve good HHS, a low incidence of complications at 12 months, a high survivorship of PAO, and satisfactory radiographic outcomes. A geographically isolated low-volume center and surgeon were able to achieve reliable and comprehensive PAO followup enabling worst-case analysis of PAO survivorship. A structured distant-mentorship program may be a suitable method for initially learning and continuing to perform low-volume complex surgery in a geographically isolated region. Future studies should investigate the reproducibility of such a mentorship program for performing complex PAO and attempt to identify optimal solutions for the maintenance of surgical expertise in geographically isolated regions performing low-volume complex surgical procedures.

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References

1. Badawy M, Espehaug B, Indrekvam K, Engesaeter LB, Havelin LI, Furnes O. Influence of hospital volume on revision rate after total knee arthroplasty with cement. *J Bone Joint Surg Am*. 2013; 95:e131.
2. Begg CB, Cramer LD, Hoskins WJ, Brennan MF. Impact of hospital volume on operative mortality for major cancer surgery. *JAMA*. 1998;280:1747-1751.
3. Biedermann R, Donnan L, Gabriel A, Wachter R, Krismer M, Behensky H. Complications and patient satisfaction after periacetabular pelvic osteotomy. *Int Orthop*. 2008;32:611-617.
4. Bilimoria KY, Bentrem DJ, Feinglass JM, Stewart AK, Winchester DP, Talamonti MS, Ko CY. Directing surgical quality improvement initiatives: comparison of perioperative mortality and long-term survival for cancer surgery. *J Clin Oncol*. 2008;26: 4626-4633.
5. Bozic KJ, Maselli J, Pekow PS, Lindenauer PK, Vail TP, Auerbach AD. The influence of procedure volumes and standardization of care on quality and efficiency in total joint replacement surgery. *J Bone Joint Surg Am*. 2010;92:2643-2652.
6. Broughton NS, Brougham DI, Cole WG, Menelaus MB. Reliability of radiological measurements in the assessment of the child's hip. *J Bone Joint Surg Br*. 1989;71:6-8.
7. Clohisy JC, Ackerman J, Baca G, Baty J, Beaule PE, Kim YJ, Millis MB, Podeszwa DA, Schoenecker PL, Sierra RJ, Sink EL, Sucato DJ, Trousdale RT, Zaltz I. Patient-reported outcomes of periacetabular osteotomy from the prospective ANCHOR cohort study. *J Bone Joint Surg Am*. 2017;99:33-41.
8. Clohisy JC, Barrett SE, Gordon JE, Delgado ED, Schoenecker PL. Periacetabular osteotomy for the treatment of severe acetabular dysplasia. *J Bone Joint Surg Am*. 2005;87:254-259.
9. Clohisy JC, Carlisle JC, Trousdale R, Kim YJ, Beaule PE, Morgan P, Steger-May K, Schoenecker PL, Millis M. Radiographic evaluation of the hip has limited reliability. *Clin Orthop Relat Res*. 2009;467:666-675.
10. Clohisy JC, Nunley RM, Curry MC, Schoenecker PL. Periacetabular osteotomy for the treatment of acetabular dysplasia associated with major aspherical femoral head deformities. *J Bone Joint Surg Am*. 2007;89:1417-1423.
11. Clohisy JC, Schutz AL, St John L, Schoenecker PL, Wright RW. Periacetabular osteotomy: a systematic literature review. *Clin Orthop Relat Res*. 2009;467:2041-2052.
12. Cook A, Khoury A, Bagli D, McLorie GA, El-Ghoneimi A, Farhat WA. The development of laparoscopic surgical skills in pediatric urologists: longterm outcome of a mentorship-training model. *Can J Urol*. 2005;12:2824-2828.
13. 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;363:45-53.
14. Cunningham T, Jessel R, Zurakowski D, Millis MB, Kim YJ. Delayed gadolinium-enhanced magnetic resonance imaging of cartilage to predict early failure of Bernese periacetabular osteotomy for hip dysplasia. *J Bone Joint Surg Am*. 2006;88:1540-1548.
15. Dahl LB, Dengso K, Bang-Christiansen K, Petersen MM, Sturup J. Clinical and radiological outcome after periacetabular osteotomy: a cross-sectional study of 127 hips operated on from 1999-2008. *Hip Int*. 2014;24:369-380.
16. Farhat W, Khoury A, Bagli D, McLorie G, El-Ghoneimi A. Mentored retroperitoneal laparoscopic renal surgery in children: a safe approach to learning. *BJU Int*. 2003;92:617-620; discussion 620.
17. 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;232:26-36.
18. Grammatopoulos G, Wales J, Kothari A, Gill HS, Wainwright A, Theologis T. What is the early/mid-term survivorship and

functional outcome after Bernese periacetabular osteotomy in a pediatric surgeon practice? *Clin Orthop Relat Res*. 2016;474: 1216-1223.
19. Harris WH. Traumatic arthritis of the hip after dislocation and acetabular fractures: treatment by mold arthroplasty. An end-result study using a new method of result evaluation. *J Bone Joint Surg Am*. 1969;51:737-755.
20. Hartig-Andreasen C, Troelsen A, Thillemann TM, Soballe K. What factors predict failure 4 to 12 years after periacetabular osteotomy? *Clin Orthop Relat Res*. 2012;470:2978-2987.
21. Holm T, Johansson H, Cedermark B, Ekelund G, Rutqvist LE. Influence of hospital- and surgeon-related factors on outcome after treatment of rectal cancer with or without preoperative radiotherapy. *Br J Surg*. 1997;84:657-663.
22. Howie DW, Beck M, Costi K, Pannach SM, Ganz R. Mentoring in complex surgery: minimising the learning curve complications from peri-acetabular osteotomy. *Int Orthop*. 2012;36:921-925.
23. Hussell JG, Rodriguez JA, Ganz R. Technical complications of the Bernese periacetabular osteotomy. *Clin Orthop Relat Res*. 1999;363:81-92.
24. Katz JN, Barrett J, Mahomed NN, Baron JA, Wright RJ, Losina E. Association between hospital and surgeon procedure volume and the outcomes of total knee replacement. *J Bone Joint Surg Am*. 2004;86:1909-1916.
25. Kosuge D, Cordier T, Solomon LB, Howie DW. Dilemmas in imaging for peri-acetabular osteotomy: the influence of patient position and imaging technique on the radiological features of hip dysplasia. *Bone Joint J*. 2014;96:1155-1160.
26. Larson AN, Rabenhorst B, De La Rocha A, Sucato DJ. Limited intraobserver and interobserver reliability for the common measures of hip joint congruency used in dysplasia. *Clin Orthop Relat Res*. 2012;470:1414-1420.
27. Malviya A, Dandachli W, Beech Z, Bankes MJ, Witt JD. The incidence of stress fracture following peri-acetabular osteotomy: an under-reported complication. *Bone Joint J*. 2015;97:24-28.
28. Manchon-Walsh P, Aliste L, Espinas JA, Prades J, Guarga A, Balart J, Biondo S, Castells A, Sanjuan X, Tabernero J, Borras JM; Catalonian Rectal Cancer Group. Improving survival and local control in rectal cancer in Catalonia (Spain) in the context of centralisation: a full cycle audit assessment. *Eur J Surg Oncol*. 2016;42:1873-1880.
29. 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;91:2113-2123.
30. Matta JM, Stover MD, Siebenrock K. Periacetabular osteotomy through the Smith-Petersen approach. *Clin Orthop Relat Res*. 1999;363:21-32.
31. Mayo KA, Trumble SJ, Mast JW. Results of periacetabular osteotomy in patients with previous surgery for hip dysplasia. *Clin Orthop Relat Res*. 1999;363:73-80.
32. Murphy S, Deshmukh R. Periacetabular osteotomy: preoperative radiographic predictors of outcome. *Clin Orthop Relat Res*. 2002; 405:168-174.
33. Murray DW, Britton AR, Bulstrode CJ. Loss to follow-up matters. *J Bone Joint Surg Br*. 1997;79:254-257.
34. Novais EN, Carry PM, Kestel LA, Ketterman B, Brusalis CM, Sankar WN. Does surgeon experience impact the risk of complications after Bernese periacetabular osteotomy? *Clin Orthop Relat Res*. 2017;475:1110-1117.
35. Porter GA, Soskolne CL, Yakimets WW, Newman SC. Surgeon-related factors and outcome in rectal cancer. *Ann Surg*. 1998;227: 157-167.
36. Severin E. Contribution to knowledge of congenital dislocation of hip joint: late results of closed reduction and arthrographic studies of recent cases. *Acta Chir Scand*. 1941;84(Suppl 63): 1–142.
37. Shervin N, Rubash HE, Katz JN. Orthopaedic procedure volume and patient outcomes: a systematic literature review. *Clin Orthop Relat Res*. 2007;457:35-41.
38. Siebenrock KA, Scholl E, Lottenbach M, Ganz R. Bernese periacetabular osteotomy. *Clin Orthop Relat Res*. 1999;363:9-20.
39. Sink EL, Leunig M, Zaltz I, Gilbert JC, Clohisy J; Academic Network for Conservational Hip Outcomes Research Group. Reliability of a complication classification system for orthopaedic surgery. *Clin Orthop Relat Res*. 2012;470:2220-2226.
40. Steppacher SD, Tannast M, Ganz R, Siebenrock KA. Mean 20-year followup of Bernese periacetabular osteotomy. *Clin Orthop Relat Res*. 2008;466:1633-1644.
41. Tönnis D, Legal H, Graf R. *Congenital Dysplasia and Dislocation of the Hip in Children and Adults.* Berlin, Germany: Springer-Verlag; 1987.
42. Trousdale RT, Ekkernkamp A, Ganz R, Wallrichs SL. Periacetabular and intertrochanteric osteotomy for the treatment of osteoarthrosis in dysplastic hips. *J Bone Joint Surg Am*. 1995;77:73-85.
43. Trumble SJ, Mayo KA, Mast JW. The periacetabular osteotomy. Minimum 2 year followup in more than 100 hips. *Clin Orthop Relat Res*. 1999;363:54-63.
44. 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;475:396-405.
45. Wells J, Schoenecker P, Duncan S, Goss CW, Thomason K, Clohisy JC. Intermediate-term hip survivorship and patient-reported outcomes of periacetabular osteotomy: the Washington University experience. *J Bone Joint Surg Am*. 2018;100:218-225.
46. Wiberg G. Studies an dysplastic acetabula and congenital subluxation of the hip joint with special reference to the complication of osteoarthritis. *Acta Chir Scand*. 1939;83:5–135.
47. Yasunaga Y, Takahashi K, Ochi M, Ikuta Y, Hisatome T, Nakashiro J, Yamamoto S. Rotational acetabular osteotomy in patients forty-six years of age or older: comparison with younger patients. *J Bone Joint Surg Am*. 2003;85:266-272.
48. Yiv BC, Saidin R, Cundy PJ, Tgetgel JD, Aguilar J, McCaul KA, Keane RJ, Chan A, Scott H. Developmental dysplasia of the hip in South Australia in 1991: prevalence and risk factors. *J Paediatr Child Health*. 1997;33:151-156.
49. Zaltz I, Baca G, Kim YJ, Schoenecker P, Trousdale R, Sierra R, Sucato D, Sink E, Beaule P, Millis MB, Podeszwa D, Clohisy JC. Complications associated with the periacetabular osteotomy: a prospective multicenter study. *J Bone Joint Surg Am*. 2014;96: 1967-1974.