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Pyrolytic carbon head shoulder arthroplasty: CT scan glenoid bone modeling assessment and clinical results at 3-year follow-up

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Background: The aim of this study is to report the radiological glenoid modifications and clinical outcomes at 3 years mean follow-up of hemi shoulder arthroplasty (HA) with pyrocarbon (PYC) humeral head. Our hypothesis was that the PYC implants would provide good outcomes without major glenoid erosion. Additionally, we hypothesized that HA-PYC allowed for remodeling of the bone.
Methods: Patients underwent HA with PyC humeral head for treatment of primary or secondary osteoarthritis, excluding post-traumatic cases. All patients had a Constant Score assessed preoperatively and at the last follow-up. Preoperative and postoperative computed tomography scans at the last follow-up were performed to achieve 3-dimensional reconstructions of the scapulae. Deformities of the glenoid surface were analyzed as a distance differential between postoperative and preoperative to investigate potential bone remodeling vs. glenoid erosion. The subluxation index (SLI) was measured.
Results: We included 41 patients implanted with a HA-PYC. Average age at the time of implant was 63.8 (40 to 79 years). All patients were followed for ≥2 years with an average follow-up of 36.3 months (24 to 60 months). Constant Scores increased from 34 at baseline to 80 at the last follow-up points on average ($P < .01$). Return to work rate was 100% and 96% had resumed their physical activity. Ten (77%) of the 13 patients with posterior head subluxation had normalized their SLI. Furthermore, no significant differences were detected between the individuals having corrected their posterior subluxation and the others (preoperative SLI between 0.45 and 0.55). Glenoid wear is less than 0.6 mm at 3 years mean follow-up, ie, 5 times less than metallic implants. A tendency to recenter the head in the anteroposterior plane was found in type B glenoid, without increased erosion of the glenoid, with very good clinical results. We did not find any difference according to age or glenoid type for clinical and radiological results.
Conclusion: HA-PYCs give, in the short term, excellent clinical results in terms of pain and function. The development of a precise and objective measurement method has made it possible to demonstrate that the glenoid surface is the site of modifications that may be part of bone remodeling or progression of the osteoarthritis disease.

Anatomic shoulder replacement for surgical treatment of glenohumeral osteoarthritis with functional rotator cuff can be performed by total shoulder arthroplasty (TSA), hemi shoulder arthroplasty (HA), or reverse TSA. The overall number of these procedures has increased by 319% since 1993 and still increases steadily by 10.6% each year.[14] Survival rate of TSA is usually high (84% at 20-year follow-up).[56] The most frequently observed complication is glenoid loosening in 14.3% of cases,[25] especially in young patients.[15] Malposition and particularly retroversion of the glenoid implant is a high-risk factor for early loosening.[28-30] Higher complication and revision rates for glenoid loosening[39,62] are reported in B and C glenoids according to the Walch classification.[60] The risk of glenoid loosening and posterior instability is over 44% if the glenoid is retroverted beyond 27°.[61] Several options are available to correct this retroversion, notably asymmetric reaming, grafting, or reverse TSA to address posterior bone defects in the case of severe deformations. However, all these options involve

Institutional review board approval was not required as this was a retrospective study of patients whose surgery followed validated techniques and no unnecessary invasive examinations were performed.

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high rates of complications and failures,[17] disappointing functional results,[29] and high revision rates.[39,62] Glenoid loosening sometimes leads to large bone defects, thereby complicating revision surgery.[45,47] In young patients, known to be more active, characterized by higher functional demand and longer life expectancy,[19,51] significant stress can lead to premature loosening of the glenoid implant.[15,24] However, previous studies have shown the advantages of TSA vs. HSA on pain, functional characteristics, and survival.[3,16,18,57] Glenoid erosion is the main complication of HA and is as common as glenoid loosening in TSA. It is associated with impaired function and poor long-term results in more than 60% of cases.[37] Functional results in these surgical revisions are lower than in total primary arthroplasties.[10,42,56] Lower functional outcomes and lower survival rates are reported in primary osteoarthritis with B and C glenoids.[36,37] Ensuring, quality of life, and restoring long-term function while preserving glenoid bone stock therefore remains challenging. Pyrocarbon (PYC) is an inert and biocompatible material[20] with Young's modulus similar to cortical bone.[27] It allows optimal stress transmission to the bone, unlike metal or ceramic. It is wear-resistant,[50] with excellent very long-term survival[40] and good clinical outcomes in upper limb surgery.[35,48,49,53] Its surface absorbs phospholipids, which promotes good sliding.[21] In vitro, PYC damage to bone is less than those caused by chrome-cobalt[32] and induces production of type II collagen, an essential component of the cartilaginous matrix.[26] The aim of this study is to report the radiological glenoid modifications and clinical outcomes at 3 years mean follow-up of HA with PYC humeral head.

Materials and methods

Study design

We retrospectively included patients who underwent HA with PYC humeral head for glenohumeral osteoarthritis, with a mean follow-up period of 3 years. We included patients with either glenohumeral primary or secondary arthritis. Patients who received previous surgery for cuff pathology and instability were included. All types of glenoid erosion according to Walch (A, B, or C) were accepted.

In our practice, every patient with arthritis and an intact rotator cuff was treated with a PYC hemiarthroplasty. During the study period, no patient received an anatomic or reverse TSA.

We excluded patients who underwent previous shoulder arthroplasty. All patients included in this study gave written informed consent and were informed of the innovative nature of this implant.

Patient population

We conducted a monocentric, retrospective study of patients who underwent HA with PyC head (Tornier SAS, Montbonnot, France) between January 2014 and December 2017. All procedures were performed by the same surgeon.

Surgical technique

Every procedure was performed in a half-sitting position, under general and locoregional anesthesia, through a deltopectoral approach with tenotomy of the subscapularis tendon. The tendon was sutured with nonabsorbable heavy-gauge thread at the end of surgery. Every patient had a tenotomy of the long head of the biceps when it was present. In young patients (<65 years old), a tenodesis was performed. Each intervention was 3-dimensionally (3D) planned using BlueprintTM software (Tornier SAS, Montbonnot, France). Humeral head osteotomy was performed at the anatomic neck level after osteophyte removal. The Aequalis Ascend Flex stem (Tornier-Wright, Memphis, TN, USA) was implanted in all patients. The diameter of the PYC head was sized with native head and varied between 39-14 mm and 54-23 mm. No reaming of the glenoid was performed. Pridie microperforations[43] were performed systematically with labrum and capsule release. No humeral stem was cemented.

Clinical and radiological assessment

Preoperative and postoperative clinical assessments were performed using a Constant Score.[13] Patient satisfaction was measured using a simple verbal scale (4 items: very satisfied, satisfied, dissatisfied, and very dissatisfied). Preoperative radiological assessments were systematically performed on axillary and anteroposterior radiographic views (external, neutral, and internal rotation). Preoperative computed tomography (CT) scans were used to evaluate the glenoid morphology according to the Walch classification[60] and to perform 3D planification with BluePrint Software. Similar radiological evaluations were systematically performed at the last follow-up. In all cases, a preoperative MRI was performed to evaluate the cuff.

Postoperative rehabilitation

All patients followed the same standard rehabilitation protocol. Immobilization only for pain was prescribed for one month. Rehabilitation was started immediately, consisting of active and passive mobilization, with external rotation of elbow to the body limited to 30 degrees and active internal rotation prohibited while the subscapularis tendon healed. After 3 weeks postoperative, immobilization was removed, no limitations in range of motion for active and passive movements.

Quality of humeral reconstruction and subluxation index

Subluxation index (SLI) of the humeral head was measured preoperatively and postoperatively using the line method with reference to the scapula axis.[31] Preoperative glenoid version was also measured and glenoid type was classified according to the Walch classification.[4,60] For type "B" glenoid, intermediate glenoid was used to make the measurement.[52] Anatomical plane of the scapula (glenoid center, trigonum, and lowest point of scapula) was used as a reference. [34] Native axial scanner sections are perpendicular to the thorax but not necessarily to the scapula axis. Scapula anatomical plane was therefore systematically determined before taking measurements so that axial sections were orthogonal to it. Quality of humeral reconstruction was assessed on frontal scanner reconstruction. Proximal humerus has 3 invariant extra-articular bony landmarks: lateral cortex below upper tuberosity, the rotator cuff footprint, and medial calcar at the level of anatomical neck.[64] From these 3 landmarks, a circle may be drawn to predict radius and rotation center of the original humeral head. This is useful to determine if prosthetic reconstruction correctly restores the patient's anatomy. On the postoperative scanner, the median frontal slice was determined in order to draw 2 circles: the first circle was drawn from the 3 invariant landmarks (anatomical circle), and the second corresponded to PyC curvature implant (circle method-fit). A 2-dimensional orthonormal landmark was created, with the center of anatomical circle as point of origin (Fig. 1). The radii of each circle and circle center displacements were measured in millimeters. A center of rotation deviation exceeding 3 millimeters was considered clinically significant. This deviation could be attributed to an inappropriate head size or a suspended humeral stem of unsuitable cut.[2]

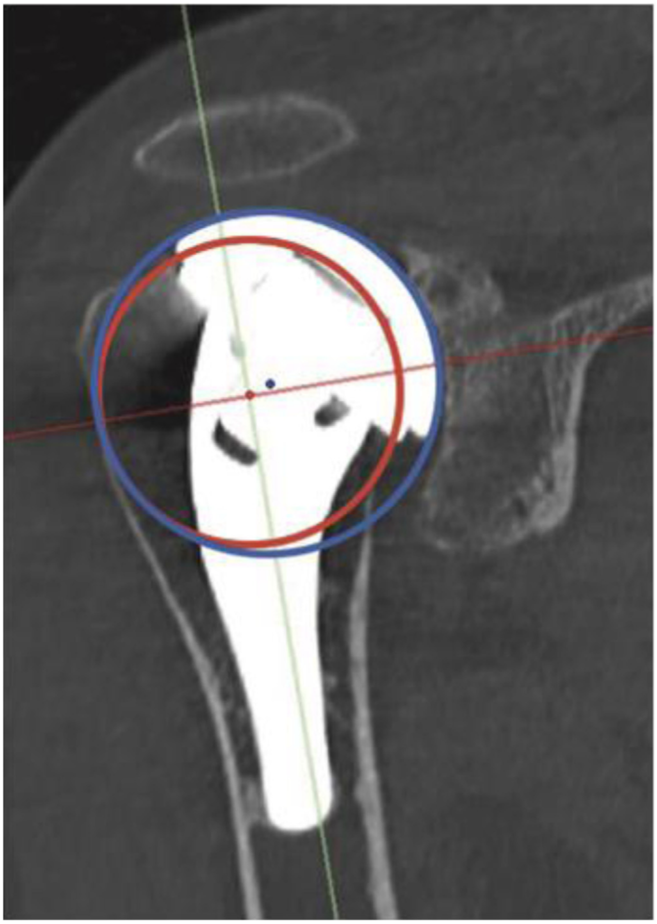

Figure 1 Red = anatomic circle with center used as mark, Blue = humeral head circle.

3D tomodensitometric analysis

CT scans were performed in submillimeter sections (625 μm thick) (Fig. 2). The resolution in the axial plane was 390 μm. A segmentation of the preoperative and postoperative scapulae was carried out from the DICOM files of the scanners using Mimics software (v. 22.0, Materialize, Leuven, Belgium) validated to reconstruct 3Ds of the scapulae.[8] Segmentation tools were used to reconstruct the scapula. At the level of the glenoid, the segmentation was carried out manually, pixel by pixel, in order to obtain the finest possible reconstruction. Scapulae were exported as an STL file to the computer-aided design software 3-Matic (v. 14.0, Materialize, Leuven, Belgium). For each patient, the preoperative and postoperative scapulae were brought closer in space manually, then automatically readjusted using an iterative closest point algorithm.[5] The iterative closest point algorithm iteratively assigned matches between source points (preoperative reconstruction) and target points (postoperative reconstruction) and minimized the distance between points of each pair created at each iteration. Precision of the two objects was between 200 and 300 μm. Distances between surface of preoperative scapula, defined as the reference, and surface of postoperative scapula were calculated. A first analysis was performed on the entire scapula to verify that the distribution of distances followed a normal law centered on zero. A second analysis was performed on the glenoid region only. The two delimited glenoid surfaces were then isolated in order to perform the distance analysis. The postoperative glenoid was compared to the preoperative glenoid which constituted the reference. Results were in millimeters. Positive distance therefore indicates a creation of matter and a negative distance indicates a loss of matter. To highlight the distribution of glenoid deformities, segmentation with a color scale was used.

Data collection and statistical analysis

Descriptive statistics were used to present patient characteristics. Continuous variables were described according to mean values, standard deviation, and extrema. In order to facilitate the representation of these results, some cases were expressed in box-plots form. Categorical variables were expressed in terms of absolute frequencies and/or percentages. The Wilcoxon test was performed on paired nonparametric variables. If these were unpaired, the Mann-Whitney test was used. Student's test was preferred for parametric variables. Statistical analyses were carried out using R language. Significant threshold for all tests was set at 0.05.

Results

Population

Between January 14 and December 2017, 67 patients underwent HA with PyC humeral head for treatment of primary or secondary osteoarthritis, excluding post-traumatic cases. Forty-one patients were included. Follow-up was available for 43 HAs. Series included 21 women (50.5%) and 20 men (49.5%), with a mean age at surgery of 63.8 ± 8.3 years (range, 40-79). The mean follow-up was 36.3 ± 11.6 months (range, 24-60). Indications for HA included primary osteoarthritis, osteoarthritis secondary to instability, and osteonecrosis in 37, 4 and 2 cases, respectively. According to Walch's classification, primary osteoarthritis included 12 A1 types, 4 A2 types, 7 B1 types, 11 B2 types, and 3 C types (Table I).

Clinical outcomes

We evaluated functional outcomes and range of motion in the study population at the last follow-up. All parameters of the Constant Score significantly improved (Table II), with initial mean points of 34 ± 7 (range, 23-47) rising to 80 ± 10 points (range, 49.5-98). Table III reports our results and shows that all amplitudes were significantly improved postoperatively. Nine patients (22%) forgot all issues associated with their shoulder and were very satisfied, 27 (66%) were very satisfied with the surgery but did not forget shoulder-associated issues, and 4 (10%) were satisfied. One patient (2%) was not satisfied. The mean postoperative score was significantly higher (P = .006) in the <60 years group (87.1 points) compared to the >60 years group (77 points). This difference disappeared with a weighted Constant Score (P = .78). The mean postoperative Constant Score in the B/C group was 78.9 ± 10.3 vs 81.1 ± 10.6 points for other glenoids, showing no statistical difference. All patients with professional activities returned to work at the last follow-up. Among patients with sports activities, 23 (96%) returned to their initial physical activity.

Complications

There were no intraoperative or early postoperative complications. One patient has stiffness treated by physiotherapy. At the last follow-up, the patient's shoulder was flexible with good range of motion. The patient underwent a PyC on the contralateral shoulder two years afterward. Six patients (14%) presented a supraspinatus tendinopathy at the last follow-up without subscapularis tendinopathy. The mean age for female patients was 66 (range, 57-77). The mean Constant Score was 65 ± 11 points (49.5-78 points) with

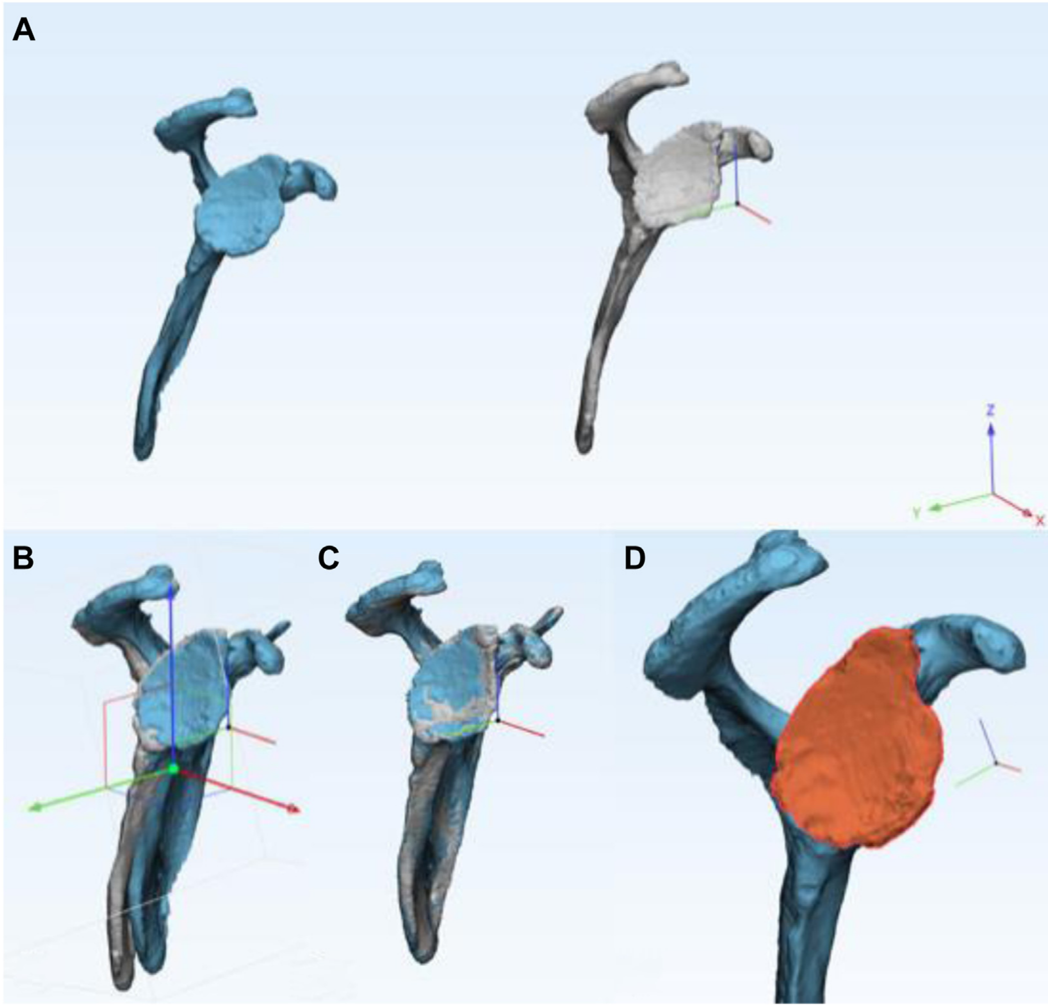

Figure 2 (a) Importation of the 2 STL files corresponding to preoperative and postoperative scapulae, (b) Manual reconciliation of the 2 scapulae, (c) Adjustment by ICP, (d) Selection of the glenoidian surface.

a mean pain score of 11 ± 3 points. Mobility score was conserved (31 ± 5 points). Constant Score and its variables were significantly lower than patients without tendinopathy (Table IV). Pain was most of the time well tolerated by patients; 5 remained satisfied. The patient with the lowest Constant Score (49.5 points, 72%) was not satisfied. It was a woman, 68 years old, treated for a primary osteoarthritis with a B1 glenoid. Her postoperative SLI was reduced by 0.47. COR > 3 mm for humeral reconstruction. Pain score decreased by one point compared to the preoperative state. Range of motion was satisfactory (EAA 130°, abduction 140°, external rotation 6 points, internal rotation 6 points). There was no revision surgery. All implants were in place at the last follow-up.

Radiological outcomes and subluxation index

Twenty-four patients had a complete radiological assessment. A statistical study was performed to compare these patients and those not included in the radiological study. There were no significant differences in terms of age, gender, glenoid type, follow-up, preoperative and postoperative Constant Scores (Table V). Mean glenoid retroversion was 13° ± 9° (0°-33°). Mean preoperative SLI was 0.63 ± 0.09 (0.45-0.74). Postoperatively, mean SLI was significantly reduced to 0.52 ± 0.05 (0.45-0.63) ($P = .002$). Fifteen patients had posterior subluxation of humeral head preoperatively (SLI>0.55). Postoperatively, 11 recentered their head with a normal SLI (73%) (Fig. 3).

Humeral reconstruction outcomes

Mean humeral head center of rotation (COR) deviation was 2.8 ± 1.1 mm (1.1 mm −5.1 mm) (Fig. 4). Eight patients had excessive COR deviation (>3 mm) in superior and medial direction. Reasons for these nonanatomical reconstructions were: oversized implant for 1 patient; inadequate cut (insufficient or vertical) for 7. In addition, 3 other patients had an oversized implant without affecting COR. These 8 patients presented no complications at the last follow-up.

3D analysis

The 24 individuals are noted from A to X in Figures. C patient had an average distance of 1.48 ± 1.39 mm. These values were significantly higher than those of the other individuals ($P < .001$, unilateral test of superiority). This patient was excluded from the statistical analysis, in order not to minimize possible bone erosion. This is explained by the poor quality of the preoperative CT scan and by the presence of an aberrant ossification anterior to the glenoid, which hampered manual segmentation. The descriptive

Table I
Demographic characteristics of the 41 patients included in our study.

	Number and (%)
Age (y)	63.8
≤60 y	13 (31)
Gender, female/male	21/20
Dominant side	23 (53)
ASA score	
ASA 1	11 (27)
ASA 2	27 (66)
ASA 3	3 (7)
Diabetes	2 (5)
History of smoking	4 (10)
Previous surgery	13 (30)
Isolated BLP tenotomy	4
BLP tenodesis	1
Acromioplasty + tenotomy	3
Bankart	2
Latarjet intervention	3
Occupational characteristic	11 (27)
Nonmanual occupation	6
Manual occupation	2
Manual occupation, heavy duty	3
Physical activity prior to diagnosis	24 (56)
Diagnosis	
Primary omarthrosis	37 (86)
Omarthrosis secondary to instability	4 (9)
Aseptic ON	2 (5)
Pridie	36 (84%)

BLP, biceps long portion; *ON*, osteonecrosis.

statistics of values are shown in Fig. 5. Postoperative glenoids were represented according to a color scale (Fig. 6) with the red zones corresponding to the values higher than the 9th decile and the blue zones to the values lower than the 1st decile. Areas where distances were the most positive (in red) were located on the periphery of the contact surface with the PyC head. Areas where distances were the most negative (in blue) were located opposite to the humeral head. Average distance was -0.3 ± 0.7 mm for patients < 60 years old and -0.7 ± 0.9 mm for > 60 years old. This difference was not significant ($P = .22$). Patients who corrected their posterior subluxation of the humeral head did not have a significantly greater deformity than the others (0.3 ± 0.6 mm and -0.7 ± 0.9 mm, $P = .53$, respectively). Also, there was no difference according to glenoid type ($P = .75$) or SLI ($P = .6$). Difference between patients without anatomical prosthetic reconstruction and the others was also not significant ($P = .92$).

Discussion

This study reports short-term radio-clinical outcomes of shoulder HA using PyC implants at a mean follow-up of 3 years with an original 3D analysis of glenoid deformities. Results confirm a reduction of pain and significant improvement of function with excellent overall satisfaction and show a recentering tendency of the prosthetic head in B and C glenoid. At the mean follow-up, the glenoid wear was less than 0.3 mm, and bone ingrowth was sometimes observed, especially in cases of head recentering. Short-term functional outcomes in our population seem to be equivalent or even higher than those reported for TSA procedures, with a mean Constant Score of 80 ± 10 points.[38] Only two previous surveys have reported outcomes for these hemiarthroplasties[12,22] In these studies, the mean postoperative Constant Score was slightly lower than ours (75 ± 17 points) at a shorter mean follow-up (26 ± 3 months). A meta-analysis[11] reported outcomes of more than 1500 TSA procedures for primary osteoarthritis with a mean follow-up of 3.7 years, longer than that of our series. The mean Constant Score was 70 points postoperatively. Another study[44] reports outcomes of HAs with metal in primary osteonecrosis or primary osteoarthritis with a mean Constant Score of 64.4 ± 19 points, with a minimum of 2-year follow-up. In our study, the mean postoperative Constant Score was 78.9 ± 10.3, even in the B and C glenoid groups, with no inferior results compared to the A group. These good clinical results appear to be better than those previously reported in available literature[36,37] and are encouraging for management of this glenoid type. Postoperative range of motion in our series was excellent: Anterior elevation 162 ± 19° and abduction 151 ± 26° (gain of 66 ± 29° et 91 ± 33°, respectively). These results are consistent with other studies comparing the same prosthesis type,[12,22] but superior to meta-analyses of randomized trials analyzing results of HA vs. TSA[7] report a mean improvement in anterior elevation of 43° for TSA and 31° for HA at 2-year follow-up.

However, studies included in this meta-analysis had more heterogeneous series than ours, which may explain this difference. Subjectively, patients were very satisfied (88%) or satisfied (10%) after surgery. Available studies report similar short-term satisfaction rates for TSA and HA.[9,38,44] In our series, only one patient was not satisfied. The Constant Score was improved, rising from 25/100 preoperatively to 49.5/100 points postoperatively. Anterior elevation and abduction increased from 60° and 30° to 130° and 140°, respectively. Despite this, the subjective result remained poor due to a demanding patient who practiced bodybulding and had a persistant supraspinatus tendinopathy. Our results are comparable with those observed in TSA series. In a randomized trial [38] comparing HA vs. TSA, the Constant Score was 67.1 ± 19.6 points in the HA group and 70.8 ± 17.2 points in the TSA group after 2-year

Table II
Preoperative and postoperative scores, net gain (mean ± standard deviation).

	Preoperative (mean ± STD)	Postoperative (mean ± STD)	Net gain (mean ± STD)	*P*
Pain (points/15)	7.5 ± 2	13.5 ± 2	6 ± 3	<.001
Activity (points/20)	9 ± 2	19 ± 1	11 ± 2	<.001
Mobility (points/40)	15 ± 5	35 ± 4	20 ± 5	<.001
Strength (points/25)	2 ± 3	12 ± 7	10 ± 6	<.001
Gross Constant (points/100)	34 ± 7	80 ± 10	46 ± 10	<.001
Weighted Constant (%)	43 ± 9	107 ± 15	64 ± 15	<.001

Table III
Preoperative, postoperative circular amplitudes, and gain in degrees or points according to Constant's Score (mean ± standard deviation).

	Preoperative (mean ± STD)	Postoperative (mean ± STD)	Net gain (mean ± STD)	*P*
AFE (°)	94 ± 24	162 ± 19	66 ± 29	<.001
ABD (°)	60 ± 21	151 ± 26	91 ± 33	<.001
ER (points/10)	4 ± 2.5	9.5 ± 1	5 ± 2.5	<.001
IR (points/10)	3 ± 1.5	7.5 ± 2	4 ± 2	<.001

AFE, active forward elevation; *ABD*, abduction; *ER*, external rotation; *IR*, internal rotation.

Table IV
Postoperative clinical results in patients with supraspinatus tendinopathy (Wilcoxon test).

	Values (mean ± standard deviation)	*P*
Constant's Score (/100)	66 ± 11	**<.001**
- Pain (/15)	11 ± 3	**<.01**
- Activity (/20)	8 ± 2	**.002**
- Mobility (/40)	31 ± 5	.06
- Strength (/25)	6 ± 4	**.009**
Weighted Constant's Score (%)	93 ± 15	**.02**

Table V
Characteristics of patients who underwent radiological evaluation and of those excluded (OA = osteoarthritis), Mann-Whitney statistical test (gender, age, duration of follow-up, Constant's Score) and χ2 test of independence (diagnosis).

	Patients included in the radiological study (n = 24)	Patients not included in the radiological study (n = 17)	*P*
Male patients	10	10	
Age (years, mean ± standard deviation)	62.9 ± 9.7	65.3 ± 6	.68
Follow-up (months, mean ± standard deviation)	35.8 ± 10.6	36.4 ± 12.7	.66
Preoperative Constant's Score (points)	35 ± 7	33 ± 7	.63
Postoperative Constant's Score (points)	80 ± 12	80 ± 9	.7
Diagnosis	Primary OA - A1 = 6 - A2 = 2 - B1 = 6 - B2 = 6 - C = 1 Secondary OA - ON = 1 - post-instability = 2	Primary OA - A1 = 6 - A2 = 2 - B1 = 1 - B2 = 5 - C = 2 Secondary OA - ON = 1 - post-instability = 2	.42

follow-up. Difference between the two groups was not significant. We can however notice in this series the inclusion of post-traumatic osteoarthritis, usually showing lower results. Clinical results are comparable if we only focus on primary osteoarthritis.

Anatomical arthroplasties performed for fracture sequelae, whether HA or TSA, show poorer results.[6,41,55] We decided to exclude this population from our study in order to keep a homogeneous population. Rate of return to work and sport was excellent, suggesting that this type of prosthesis would be suitable for the young and active population. No revisions were performed at the last follow-up. Six patients presented supraspinatus tendinopathy, which explains a significant decrease in the functional score. These patients had an anatomical reconstruction of proximal humerus, therefore overstuffing does not explain this symptom. We assume that this complication is related to the preoperative quality of rotator cuff tendons, in relation with specific terrain in those patients (age, overuse). This complication of HA is known, but the rate in our series was higher than values in literature. Other authors[12,22] find implant survival between 92 and 95.3% at 2-year follow-up.

Revisions were motivated by secondary rotator cuff tear or persistent glenoid pain. In the literature, rate of rotator cuff tendinopathy after metal HA ranges from 1 to 14%.[1,18,25,38] These tendinopathies are also known complications of TSA, with a prevalence of 2%.[63] For metal HA, implant survival rates are 90 to 96% at two years of follow-up.[23,38] However, we know that the revision rate of arthroplasty increases over time.[54] After radiological analysis, we found that 33.3% did not have optimal restoration

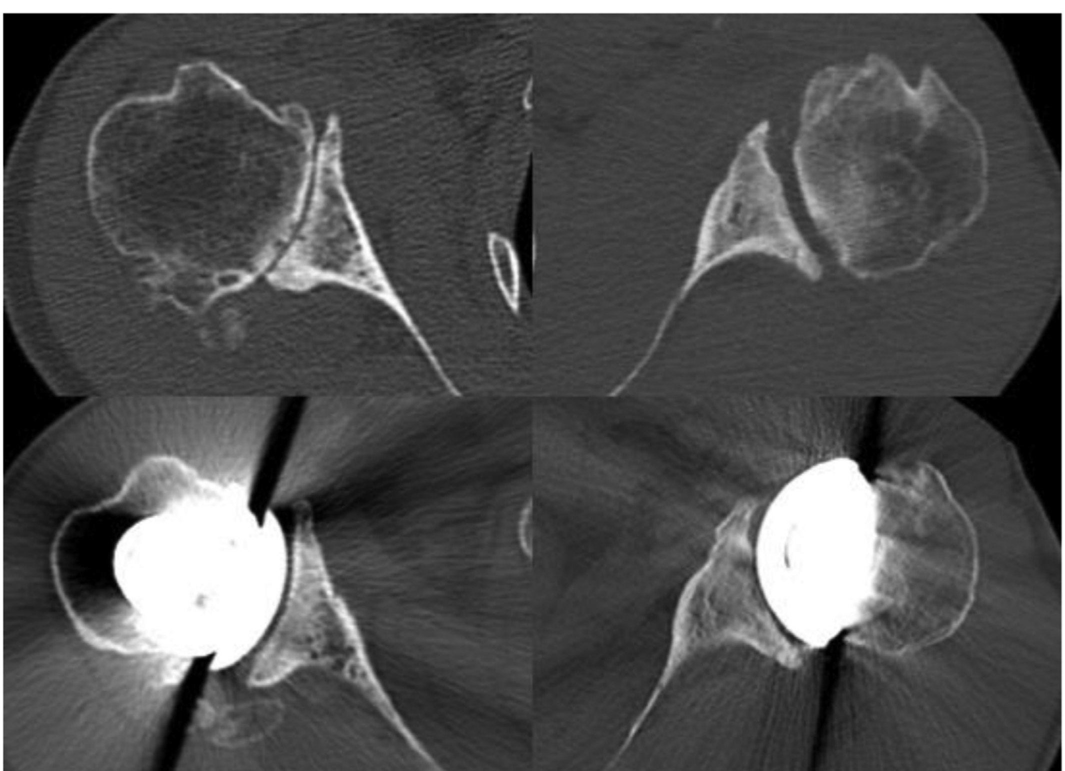

Figure 3 Individual on the left: preoperative ISL = 0.63, postoperative ISL = 0.50. Individual on the right: preoperative ISL = 0.61, postoperative ISL = 0.45.

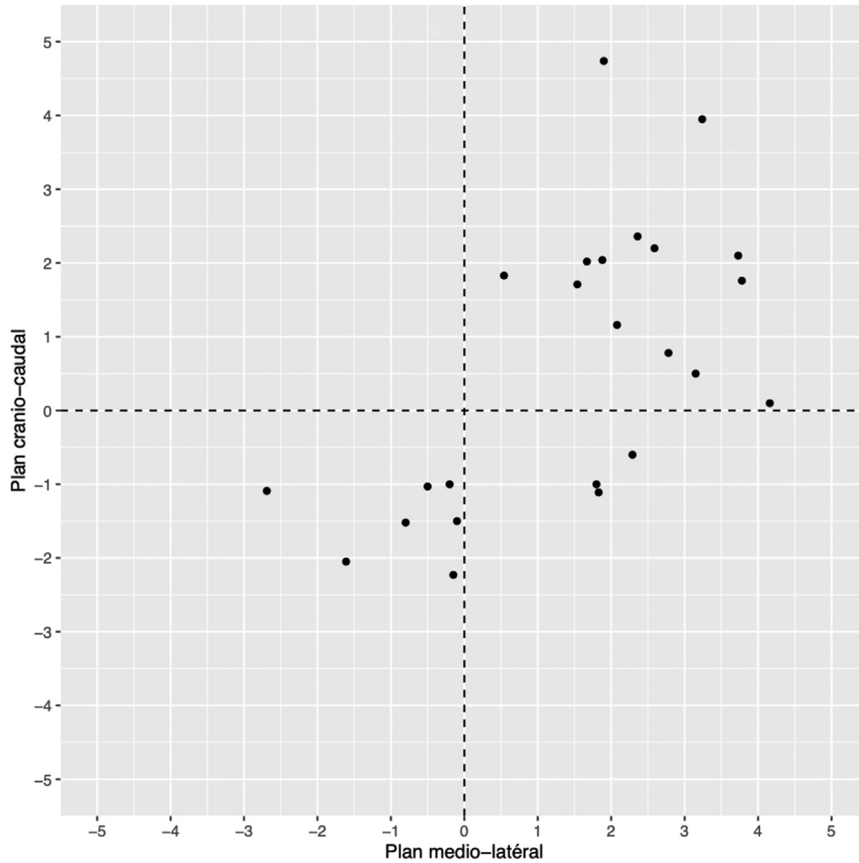

Figure 4 Shifting of the prosthetic center of rotation vis-à-vis the anatomic center of rotation (0, 0). x, mediolateral plane, y, cranio-caudal plane. Scale expressed in millimeters.

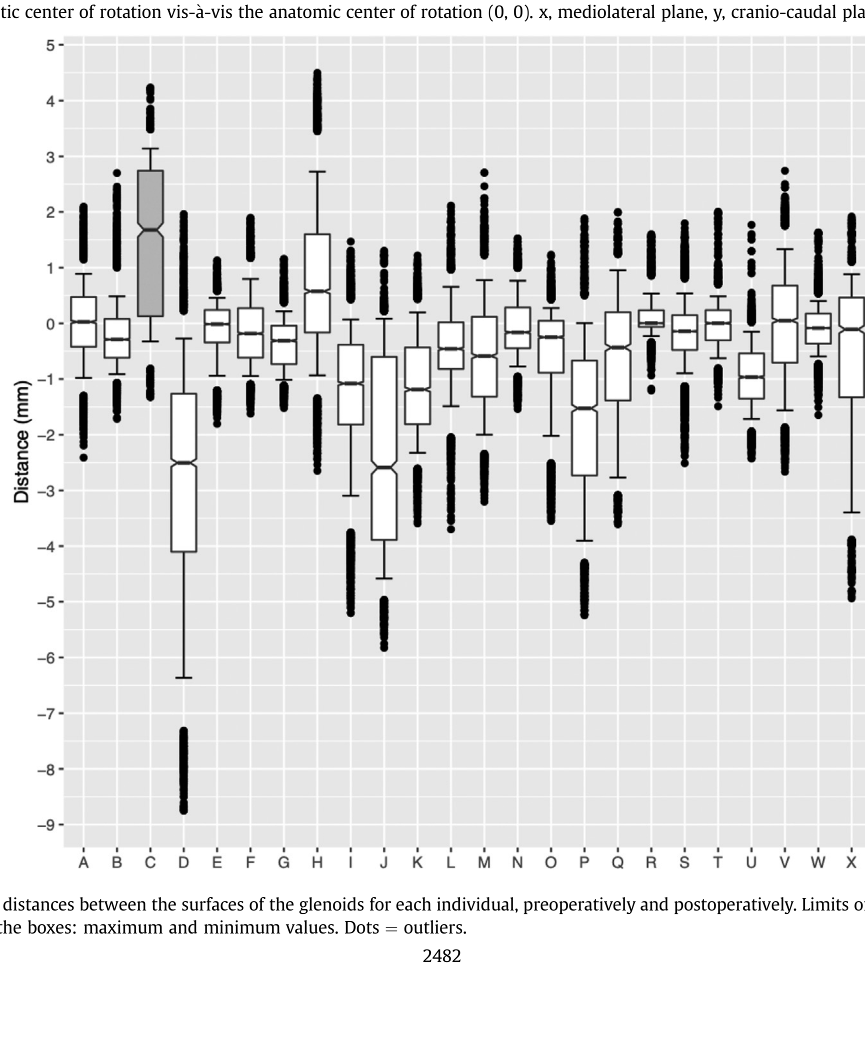

Figure 5 Box-plots showing the distances between the surfaces of the glenoids for each individual, preoperatively and postoperatively. Limits of the boxes = 1st and 3rd quartiles. Limits of the segments outside the boxes: maximum and minimum values. Dots = outliers.

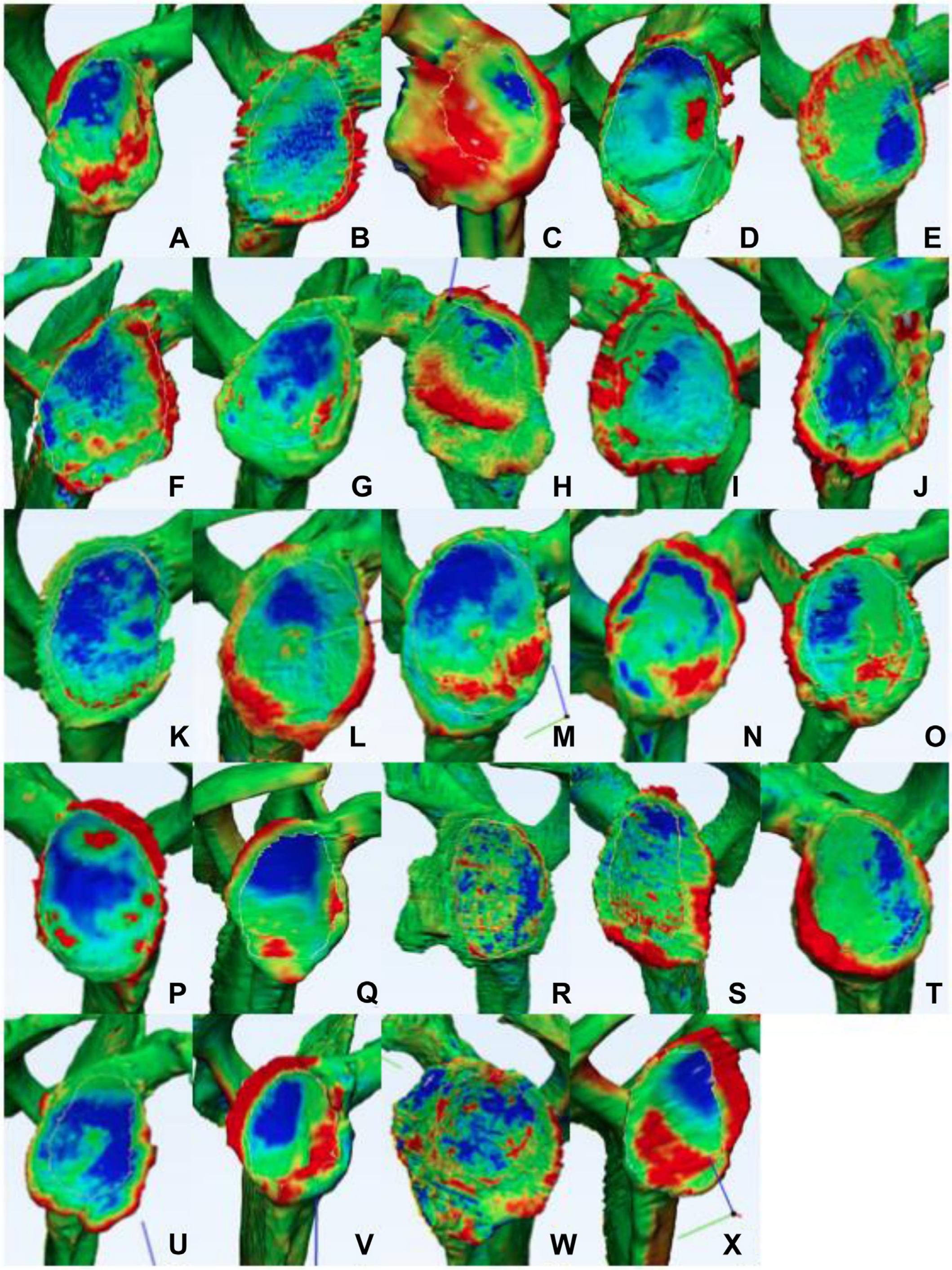

Figure 6 3D reconstructions of the postoperative glenoids in the 24 individuals. Spatial representation of the distances between the surface of postoperative glenoids compared to preoperative glenoids. The blue color corresponds to values below the first quartile (most negative distances = loss of substance). The red color corresponds to values above the third quartile (most positive distances = substance gain).

of proximal humerus anatomy. When deflected, center of rotation was medialized in all cases. This medialization may lead to "overstuffing" the joint, a source of complications such as glenoid erosion or rotator cuff tears. However, a majority of these deviations were moderate and none had clinical consequences. Other studies,[2,12] which had also compared the quality of humeral reconstructions of anatomical arthroplasties, found similar rates of deviation from the center of rotation (31.2% and 28%). Our main finding is the anteroposterior refocusing of the humeral head. Among the 15 patients with posterior subluxation of the humeral head, 11 corrected their ISL at the last follow-up and no reaming of the glenoid was performed. This was also observed by Garret et al,[22] who formulated two hypotheses formulated: PyC humeral cap allows the restoration of an anteroposterior translational movement, in particular, due to its surface chemical properties, with absorption of phospholipids forming a lubricating layer[21,59]; as an alternate explanation, PyC implant may induce a bone remodeling of the paleoglenoid, which has a lower density compared to the neoglenoid.[33] Both effects can probably be combined to explain this remodeling.

Until now, most publications studying glenoid erosion in HA used a subjective scale ranging from grade 1 to 4 (no erosion, mild, moderate, severe erosion),[58] read on plain radiographs. The method presented by Parsons et al[46] is an objective measurement using a 3D modeling pen on frontal radiographs. However, even if the X-ray images had strict quality criteria, it remains less precise than CT scan. Merolla et al[42] proposed a two-dimensional glenoid erosion scanographic measurement method allowing to measure joint space on the middle of the glenoid cut. This method does not provide an overall analysis of the glenoid surface. In addition, the preoperative joint space was not measured in order to highlight any narrowing. All these methods only allow a subjective interpretation, based on a qualitative evaluation, without taking into account the complex 3D structure of the glenoid. The method used in our study is a direct, objective, and precise measurement. This is an original method which, to our knowledge, has never been used in the field of orthopedics. It makes it possible to highlight modifications of the glenoid surface in a much finer way than an X-ray analysis. Precision of values should be evaluated considering the precision of the scanner (vertical resolution 650 μm, horizontal resolution 390 μm) and the registration of objects (200 to 300 μm). Segmentation also creates noise ie, not quantifiable. Selection of glenoid surface to be analyzed was done manually for two reasons. There is no standardized method for selecting the glenoid because of interindividual morphological variability that makes it difficult to use a reproducible technique.[33] Besides, the manual selection allows to cancel metallic artefacts. In order not to minimize a possible loss of material by taking into account zones with very positive distances, artefactual regions were not selected for analysis of the glenoid deformation surface.

However, in our study, analysis is limited by several factors. First, some glenoids presented cysts in their 3D reconstruction, thereby limiting and strongly affecting the calculation of volumes. Secondly, errors induced to obtain our 3D glenoids introduced visual noise in the reconstructions (possibly due to scanner resolution, segmentation, or registration). These noises, although tiny on a small scale, accumulated and ultimately modified the apparent volume of these objects. The main limitation of our study is the absence of a control group. Indeed, we were not able to conduct a direct comparison with patients treated with metal HA. In addition, this is a monocentric, retrospective study, and measurements were performed by a single observer (different from the operator, however). While results are encouraging, no conclusion on long-term efficacy can be drawn, and it is known that the clinical and radiological results of HA deteriorate over time for metallic implants.[7] We can however notice that the metallic implant surface worsens with time, unlike the PYC. Patient follow-up should be continued to confirm our results.

Strengths of our study reside in the homogeneity of the study group (osteoarthritis following fractures having been excluded) and the fact that all interventions were carried out by a single operator. PyC HA allows, at 3 years mean follow-up, pain relief, recovery of shoulder function, and return to professional and physical activities, regardless of age and type of glenoid. These functional outcomes are comparable to those of short-term TSA. The development of a precise and objective measurement method allowed to demonstrate that glenoid surface modifications did not reflect a simple erosion but may be part of bone remodeling with bone ingrowth zone. Moreover, we do not find increased erosion in patients with the longest follow-up period. Finally, we found a trend toward a recentering of the humeral cap in the anteroposterior plane, without increased erosion of the glenoid, associated with very good clinical outcomes in B and C glenoid.

Conclusion

PyC HA implants provide excellent short-term clinical results, without major erosion of the glenoid. They could be a solution in currently challenging cases (young, retroverted glenoids, and posterior subluxation of the head). Medium- and long-term follow-up is necessary to confirm these results.

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