Original Research

Long-term Follow-up on Revisions of a Recalled Large Head Metal-on-metal Hip Prosthesis: A Single Surgeon Series

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A R T I C L E   I N F O

A B S T R A C T

Background: In 2010, a recall was issued for a specific monoblock large head metal-on-metal (MoM) hip prosthesis due to short-term revision rates of 12%-13% (articular surface replacement, DePuy Orthopaedics, Inc., Warsaw, IN). High complication, infection, and rerevision rates for revised MoM implants have been reported. The purpose of the study is to report long-term outcomes and trend metal ion levels of this recalled MoM prosthesis from a single surgeon series.
Methods: Retrospective chart review was performed on all patients that underwent revision of large MoM hip replacements between 2010 and 2015. Pre- and post-revision Harris Hip Score (HHS), cup abduction angles, anteversion angles, and cup sizes were compared. Survivorship and HHS were the primary outcomes measured; serum cobalt and chromium levels were secondary outcomes. Multivariate linear regression was used to examine the correlation between prerevision serum metal ion levels and HHS.
Results: A total of 24 hips (21 patients) met inclusion criteria. Mean time to revision was 4.12 years ± 1.1. Mean follow-up was 10.0 years (7-11.9 years). Mean HHS increased significantly after revision from 48.5 to 89.5 ($P < .001$). Higher prerevision cobalt levels were correlated with lower prerevision HHS (cobalt $R = 0.25$; chromium $R = 0.3160$). There was no correlation with prerevision cobalt ($P = .2671$) or chromium ($P = .3160$) with postrevision HHS. Most recent metal ion testing revealed a significant decrease in both cobalt ($P = .0084$) and chromium ($P = .0115$). Survival rate is 100%.
Conclusions: Our study showed excellent survivorship and outcomes at 10 years. There were no failures for any reason including infection. This differs from previous studies and confirms excellent long-term results are possible with revision of this recalled MoM implant.

Introduction

Total hip arthroplasty (THA) remains one of the safest and most successful procedures in orthopaedics [1]. Traditional metal-on-polyethylene (MoP) hip replacements have shown a survivorship of 78% at a minimum 35-year follow-up [2]. To combat the increased wear of MoP in an increasingly younger population, metal-on-metal (MoM) THA gained popularity in the early 2000s and reached around 35% of all THAs at that time [3]. Favorable

aspects of MoM articulations included smaller wear-particle size with resultant decreased histologic response compared to the conventional MoP couplings [4]. In addition, the ability to use large femoral head implants increased the head-neck ratio and ultimately resulted in increased stability, improved range of motion, decreased femoral neck impingement and dislocation rates [4-6]. Published short- and intermediate-term results were encouraging. Several reports showed MoM articulations to have favorable outcomes similar to that of MoP with early survivorship between 93% and 97% [7-10].

In August 2010, DePuy Orthopaedics, Inc., Warsaw, IN, issued a recall for its MoM THA acetabular prosthesis and resurfacing systems (DePuy Orthopaedics, articular surface replacement [ASR] recall). The recall stemmed from early data from the National Joint

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Table 1
Revision rate for failed DePuy metal-on-metal hip replacement.

Article	% Revision	Failed implants	Mean time to revision (mo)
Langton et al. (2010) [15]	3.2% (13/418)	DePuy ASR resurfacing	41
	6% (5/87)	DePuy ASR XL THR	
Langton et al. (2011) [21]	25% (57/206)	DePuy ASR resurfacing	72
	48.8% (25/51)	DePuy ASR XL THR	
Steele et al. (2011) [22]	15.2% (16/105)	DePuy ASR XL THR	20
Rajpura et al. (2011) [23]	5.2% (2/38)	DePuy ASR resurfacing + XL THR	45
Bernthal et al. (2012) [24]	17.1% (12/70)	DePuy ASR XL THR	36
Reito et al. (2013) [25]	16% (162/1036)	DePuy ASR resurfacing + XL THR	60
Hug et al. (2013) [26]	13.1% (19/149)	DePuy ASR resurfacing	40
	12.1% (5/41)	DePuy ASR XL THR	
Cip et al. (2015) [27]	30% (30/99)	DePuy ASR XL THR	54

Registry in Wales revealing revision rates of 12%-13% with this system as opposed to the expected 5%-6% [11]. Surgeons began to describe adverse local tissue reactions (ALTRs) associated with the MoM-bearing surfaces [12]. In the literature, these have been termed metallosis, adverse reactions to metal debris, pseudotumor, and aseptic lymphocytic vasculitis-associated lesions, but may be grouped under term ALTR [13-18]. Infection and aseptic loosening were also among the complications reported to increase the failure rate of MoM bearing [17,19,20]. Several subsequent studies of this monoblock MoM THA confirmed unacceptably high rate of revision surgeries ranging from 3.2% to as high as 48.8% [15,21-27] (Table 1).

Surgical treatment strategies for failed MoM hip arthroplasties are varied. These include revision of both femoral and acetabular components, revision of acetabular component, or retention of both components, and performing an isolated dual mobility (DM) liner-head exchange [27-37]. A common strategy is to replace the acetabular component and the femoral head while retaining a well-fixed femoral stem [33,38,39]. To our knowledge, there are no studies with long-term follow-up for revisions of DePuy ASR MoM THA from a single surgeon series. The purpose of this study is to report long-term outcomes and trend metal ion levels of revised monoblock large head MoM DePuy ASR hip prosthesis.

Material and methods

Between 2006 and 2010, a single senior arthroplasty surgeon at our institution performed 107 DePuy ASR MoM THAs. As revisions of MoM prostheses began to increase, we began collecting prospective data on these patients with the approval of our hospital's institutional review board. All patients who underwent revision of the DuPuy ASR (DePuy Warsaw, Indiana) large head hip replacement system were retrospectively identified and prospectively followed. This included 36 patients undergoing 39 revision total hip arthroplasties. Patients that were deceased (3), paralyzed due to stroke (1), underwent revision elsewhere (1) or recent revision (6), and those lost to follow-up (4) were excluded from the study (Fig. 1). Recent revisions were defined as those who underwent a revision surgery within the last 3 years and did not have adequate follow-up. A total of 21 patients who underwent 24 revision surgeries were included in the final analysis (mean age = 67.2 ± 11.0 years; 11 men, 13 women; mean body mass index = 30.3 ± 5.8).

All primary THAs were done without navigation and through a standard posterolateral approach with enhanced posterior soft tissue repair [40]. Neuraxial anesthesia was the goal for all patients.
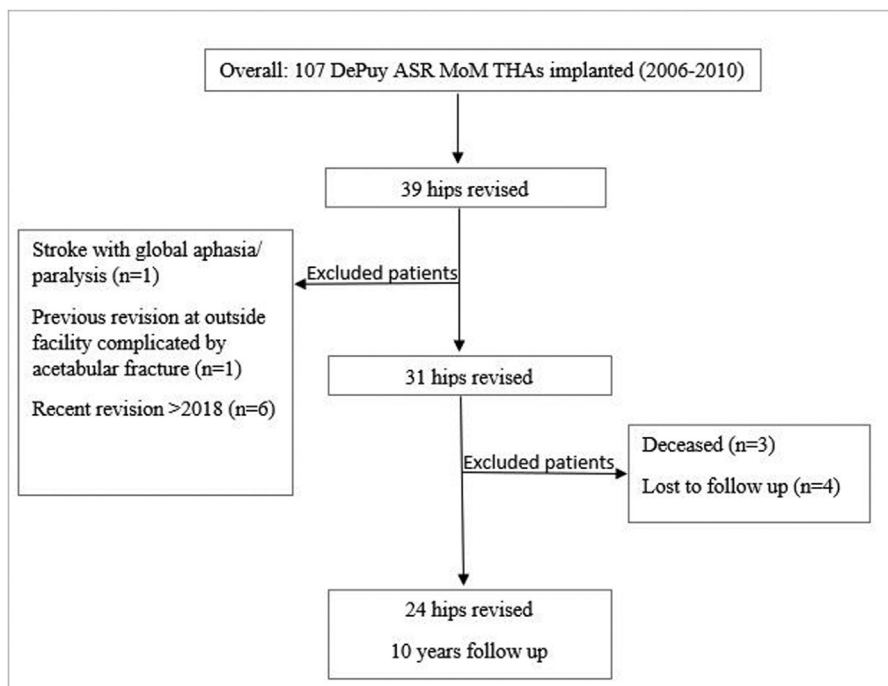

Figure 1. Follow-up flow chart.

Table 2
Indications for revision surgery, preoperative metal ion grouping, and intraoperative findings.

| Surgery number	Indications for revision	Preoperative metal ion group	Intraoperative finding
1	Elevated metal ions, effusion	High	Effusion, metallosis of soft tissue
2	Hip pain, elevated metal ions, lack of cup ingrowth, effusion	High	Effusion, lack of cup ingrowth
3	Hip pain, elevated metal ions, lack of cup ingrowth	High	Lack of cup ingrowth
4	Squeaking, elevated metal ions	High	Metallosis of soft tissue
5	Hip pain, elevated metal ions	High	Metallosis of soft tissue
6	Hip pain, elevated metal ions, lack of cup ingrowth	High	Metallosis of soft tissue, lack of cup ingrowth
7	Hip pain, elevated metal ions, lack of cup ingrowth	High	Metallosis of soft tissue, lack of cup ingrowth
8	Hip pain, pseudotumor, elevated metal ions	Moderate	Pseudotumor, metal-tinged fluid
9	Hip pain	Normal	Lack of cup ingrowth
10	Hip pain	NA	Lack of cup ingrowth
11	Hip pain, lack of cup ingrowth	Low	Lack of cup ingrowth
12	Elevated metal ions, effusion	High	Effusion, metallosis of soft tissue
13	Hip pain, elevated metal ions	Moderate	Lack of cup ingrowth
14	Pseudotumor, elevated metal ions	High	Pseudotumor, metal-tinged fluid, metallosis of soft tissue
15	Hip pain, effusion	Low	Effusion
16	Pseudotumor, elevated metal ions	Moderate	Pseudotumor, metallosis of soft tissue
17	Hip pain, lack of cup ingrowth	Low	Lack of cup ingrowth
18	Hip pain	Low	Lack of cup ingrowth
19	Hip pain, lack of cup ingrowth	Low	Lack of cup ingrowth
20	Hip pain, pseudotumor	Low	Pseudotumor, effusion
21	Hip pain, lack of cup ingrowth	Low	Lack of cup ingrowth
22	Hip pain, lack of cup ingrowth	Low	Lack of cup ingrowth
23	Hip pain, pseudotumor	Low	Pseudotumor, metal-tinged fluid
24	Hip pain	Low	Metal-tinged fluid, metallosis of soft tissue, lack of cup ingrowth

NA, not applicable.

If a neuraxial was unable to be obtained, then a general anesthetic was utilized.

Indications for revision of this failed monoblock MoM and patients' preoperative metal ion groupings are summarized in Table 2. We grouped metal ion levels as normal (<1 ppb), low (1-8 ppb), moderate (8-20 ppb), and high (>20 ppb) based on the laboratory measurements. This is our grouping based on a consensus that was derived early in the recall period. For consistency purposes, we maintained this classification. Preliminary diagnosis of pseudotumor was made based on preoperative ultrasound (US) or metal-reduction magnetic resonance imaging (MRI) and later confirmed with intraoperative findings.

The workup for all our MoM patients was consistent. All patients underwent a full history and physical examination preoperatively to rule out other extrinsic pathologies that can affect the hip such as spine- or knee-related pathologies. Patient underwent an infection workup, which included an erythrocyte sedimentation rate and C-reactive protein. Joint aspiration was performed on patients with elevated erythrocyte sedimentation rate or C-reactive protein. Cobalt (Co) and chromium (Cr) metal ion levels and plain radiographs were obtained on all patients. Patients that had pain and/or elevated metal ion levels received further imaging with either an US or MRI. Early in the study period, an US was the study of choice, which was later replaced by metal artifact reduction sequence MRI. There were no acetabular defects/wear preoperatively in any zone that required classification.

Prophylactic antibiotics (Ancef 2g and vancomycin 1g) were given to all patients prior to surgery. Patients received Ancef for 24-48 hours postoperatively based on the length of stay. All patients underwent neuraxial or general anesthesia. A similar surgical technique was utilized in all cases. An extensile posterolateral approach was utilized; specimens were sent for frozen section, pathology, and culture. The femoral stems were retained while the acetabular and femoral head components were replaced. In all cases, the femoral head was removed, and trunnion was inspected for corrosion. The femoral stem was always tested to make sure it was well-fixed and stable. The trunnion was cleaned, and the femoral prosthesis was retracted to allow access to the acetabular component. The acetabular component was removed using acetabular removal osteotomes. Once removed, the remaining acetabular bone was evaluated for adequate bone stock. Acetabulum was then reamed sequentially to bleeding bone, and press-fit revision-type acetabular component was placed. Following placement of the new acetabular cup (DePuy Pinnacle with Gription [DePuy Orthopaedics, Inc., Warsaw, IN]), a highly cross-linked polyethylene liner and zirconia-alumina matrix ceramic femoral head with a titanium taper sleeve adapter (BIOLOX Delta, CeramTec AG, Plochingen, Germany) was placed in all patients. No other levels of constraint were required at that point. The wound was then copiously irrigated with an antibiotic-impregnated solution (bacitracin + normal saline). The hip was then reduced and brought
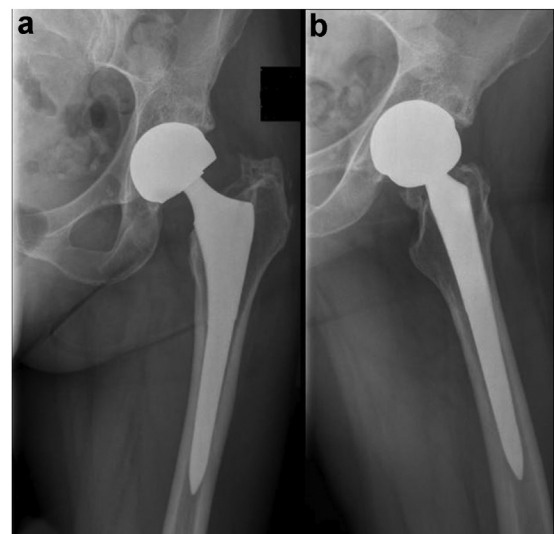
Figure 2. (a) Anteroposterior and (b) lateral typical prerevision radiographs.
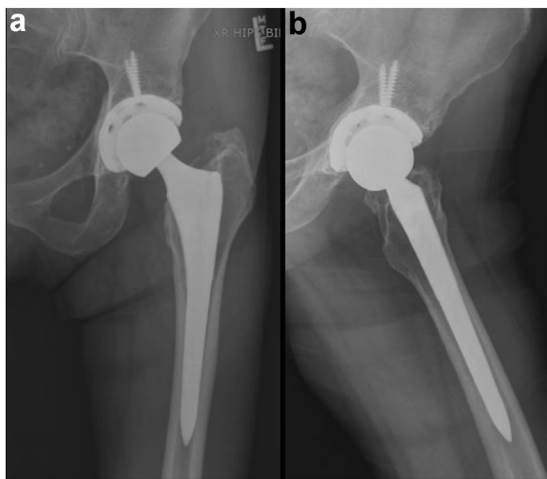
Figure 3. (a) Anteroposterior and (b) lateral radiographs postoperative revision surgery of the same patient.

through a range of motion, and stability was confirmed. Except in cases where there was extensive soft tissue excision and debridement, a posterior capsular repair was performed. In patients where the repair was not performed, an abduction brace was used for 6 weeks postoperatively. There were a total of 5 patients who required an abduction brace. On average, 2 screws ($\pm$1) were needed for proper fixation of the cup. Metal ion levels were followed periodically postoperatively. Sizes were recorded from operative reports. Please see Figures 2a and b and 3a and b for representative preoperative and postoperative radiographs, respectively.

Demographic data was collected for all patients. Complications were tracked by reviewing the electronic medical record and by patient visits and interviews. Prerevision and postrevision cup abduction and anteversion angles were measured using the EBRA-CUP software program (University of Innsbruck, Innsbruck, Austria). All patients were referred to an outside laboratory for serum cobalt and chromium level measurements. Metal ion levels were repeated after revision surgery and measured throughout follow-up. Clinical outcomes were assessed with Harris Hip Score (HHS) before and after revision surgery to measure function and pain.

We analyzed the data using the analysis of variance Wilcoxon signed rank tests (STATA v.11, College Station, TX) to evaluate the relationships between preoperative and postoperative metal ion levels and HHS.

Results

A total of 39 hips were revised (39/107) which shows that the failure rate of the DePuy ASR MoM THAs was as high as 36.4% in this study. Twenty-one patients that underwent 24 revision surgeries were included in our final analysis group. The mean time from index arthroplasty to revision was 4.12 $\pm$ 1.1 years. Mean age at primary surgery was 52.6 $\pm$ 10.5 years (range, 27-65) vs 55.5 $\pm$ 10.9 years (range, 29-69) at revision surgery. Thirteen patients were female, and 11 patients were male. The median prerevision acetabular cup size was 52 $\pm$ 3 mm (range, 50-58 mm) and head size was 46 $\pm$ 2 mm (range, 45-53 mm). The mean prerevision cup abduction angle was 46.38 $\pm$ 11.2 degrees (range, 30.6-76.3) and cup anteversion was 24.16 $\pm$ 9.8 degrees (range, 6-43.7). Mean follow-up from date of revision was 10.2 $\pm$ 1.3 years. Intraoperative findings are summarized in Table 2. In all cases, the trunnion had

Table 3
Comparison of patient characteristics pre- and post-revision.

	Prerevision	Postrevision	*P*-value
Mean Harris hip score	48.5	89.5	<.001[a]
Mean cup abduction angle (°)	46.4	40.9	.012[a]
Mean cup anteversion (°)	24.5	30.2	.02[a]
Median cup size (mm)	52	58	<.001[a]
Mean cobalt level (ppb)	40.9	2.5	.0084[a]
Mean chromium level (ppb)	15.6	6.3	.0015[a]

[a] Statistically significant.

minimal to no corrosion, and at that time, the pathology department was not performing the aseptic lymphocytic vasculitis-associated lesions grading system.

Three of 24 surgeries (12.5%) involved at least one early complication after revision of the monoblock MoM hip prosthesis. Only one complication was considered major (dislocation, 4.1%), while the remaining 2 were minor complications (trochanteric bursitis, 8.3%). The mean time from revision to complication was 18 months (range, 5-34 months). The patient had 2 recorded dislocations. The first was 15 months postoperatively and the second was 30 months postoperatively. Both dislocations occurred spontaneously as per patient history and were managed nonoperatively by closed reduction, bracing and strict hip precautions, followed by physical therapy. The patient recorder recorded no further dislocations. At the latest follow-up, there were no reoperations performed, and there were no incidences of acetabular loosening, prosthetic joint infection, nerve injury, periprosthetic fracture, wound complication, or pulmonary embolism. The total revision hip survival rate was 100% (24 of 24) at mean of 10 years.

Preoperative and postoperative HHSs were available for 20 out of 21 patients. Patients showed significant improvement with the mean HHS increasing from 48.5 to 89.5 ($P < .001$) and were 84.4 at their most recent follow-up (Table 3).

Twenty-one of twenty-four procedures had complete data for both pre- and post-metal ion levels (Table 4). Both cobalt and chromium levels significantly decreased after revision. Cobalt levels decreased from a mean of 40.9 ppb to 2.5 ppb ($P = .0084$). Chromium levels decreased from a mean of 15.6 ppb to 6.3 ppb ($P = .0015$). Higher prerevision cobalt levels were correlated with lower prerevision HHS (cobalt $R = 0.25$; chromium $R = 0.3160$). There was no correlation with prerevision cobalt ($P = .2671$) or chromium ($P = .3160$) with postrevision HHS. Cup abduction angles decreased from a mean of 46.4 degrees to 40.9 degrees ($P = .012$) upon revision, whereas the cup anteversion angle increased from 24.2 to 30.2 degrees ($P = .02$). The median cup size increased from 52 mm to 58 mm ($P < .001$) (Table 3). The median postrevision femoral head size was 36 $\pm$ 3 mm (range, 36-44 mm). At that time, we were using the largest possible head size for every acetabular cup with 36 mm being the most common.

Discussion

Certain MoM articulations in THA have resulted in unacceptably high complication rates, leading to high rates of revision surgery [15,21-27] (Table 1). Those results were comparable to our study, which showed a failure rate as high as 36.4% for the DePuy ASR MoM primary THAs. This eventually led to further studies in order to report outcomes of revision surgeries for failure of these MoM hip implants; however, they only reported short-term and intermediate outcomes (Table 5) [27-37,39,41,42]. Our study has a mean follow-up of 10 years and to our knowledge, no other study has reported such long-term outcomes except for one study by Lin et al; however, they revised a different MoM THA implant (Zimmer

Table 4
Pre- and post-revision cobalt (Co) and chromium (Cr) levels, metal ion grouping, complications postrevision surgery and other joint implants.

Surgery number	Prerevision Co level (ppb)	Prerevision Cr level (ppb)	Prerevision metal ion group	Postrevision Co level (ppb)	Postrevision Cr level (ppb)	Postrevision metal ion group	Complications postrevision surgery	Other joint implants
1	132	24.8	High	7.9	1.1	Low	None	None
2	28	NA	High	4	1.5	Low	None	Contralateral THA
3	28	NA	High	4	1.5	Low	None	Contralateral THA
4	106.3	41.3	High	7.3	13	Moderate	None	RSA
5	130	71	High	NC	NC	NA	None	None
6	110	66	High	1.7	36	High	None	Contralateral THA
7	110	66	High	1.7	36	High	None	Contralateral THA
8	11.9	1.9	Moderate	0.2	0.2	Normal	None	None
9	<1.0	<1.0	Normal	<1.0	<1.0	Normal	Trochanteric bursitis	None
10	NC	NC	NA	3.8	2.2	Low	None	TKA
11	5.8	<1.0	Low	0.8	0.4	Normal	None	Contralateral THA
12	176.3	64.8	High	3.9	24	High	None	None
13	13.1	2.2	Moderate	NC	NC	NA	None	None
14	111.3	42.5	High	0.4	9.8	Moderate	None	None
15	1.3	1.8	Low	0.2	0.3	Normal	Two dislocations	Contralateral THA
16	14.6	4	Moderate	0.4	1.1	Low	None	TKA and revision TKA
17	<1.0	1.2	Low	0.4	0.3	Normal	None	Contralateral THA
18	4.4	2	Low	4.2	0.3	Low	None	Contralateral THA
19	5.8	2.9	Low	4.2	0.3	Low	None	Contralateral THA
20	2.5	3.2	Low	0.3	0.2	Normal	None	None
21	6.8	4.8	Low	1.9	1.9	Low	None	Contralateral THA
22	5.7	3.4	Low	3.9	1.7	Low	Trochanteric bursitis	Contralateral THA, TKA
23	2.7	1.2	Low	0.3	0.3	Normal	None	Contralateral THA
24	2.1	1.9	Low	0.5	0.9	Normal	none	Contralateral THA, TKA

NC, not collected; NA, not applicable; TKA, total knee arthroplasty; THA, total hip arthroplasty; ORIF, open reduction and internal fixation; RSA, reverse shoulder arthroplasty.

Biomet, Warsaw, IN) and had 3 different surgeons [42]. In addition, most studies included revised implants from several manufacturers [28-33,35-37,39]. Furthermore, other studies had multiple surgeons involved and were not a single institution, single surgeon study, which resulted in different surgical approaches and multiple revision techniques that might have affected their outcome [28,30,32,34-37,39,41]. In our study, none of the stems were revised, and the same extensile posterior approach was performed in our institution by the same surgeon with the same implant (DePuy Pinnacle) used for revision as discussed in our technique previously.

In our series, we reported only one major complication (4.1%) at an average 10-year follow-up. This is comparable to the series of Liddle (5.2%), Pritchett (4.4%), Wyles (8%) and Cip (10%) and lower than complications reported by Liow (14%), Crawford (14%), Colacchio (17.4%), Lin (16.5%), Iqbal (18%), Stryker (20%), Jennings (27.7%), Burton (36%), Munro (38%) and Chen (40%) (Table 5) [27-37,39,41,42]. To date, we report a 100% survivorship of revision of failed large head MoM THA which has not been reported yet. Certain studies reported a survival rate above 90% and could be comparable to our study [27-31,33]. In these studies, several implants were studied, and surgical technique was not consistent throughout. [29,31,33]. The other studies performed by Liddle et al and Pritchett [28,30] were not a single institution, single surgeon study and also revised multiple implant types and yet were able to maintain low complication rates and an overall survivorship of 95%

and 96%, respectively. These studies involved short-term (30 months) [28] and midterm (61 months) [30] follow-up.

Two studies that were a single institution, single surgeon study revising one implant type were those reported by Cip et al (DePuy ASR) and Jennings et al (DePuy Pinnacle) [27,34]. Cip et al reported a complication rate of 15% and an overall survivorship of 95%, but they had 10 patients that were lost to follow-up, which is 33.3% of their sample (10/30) and had a mean follow-up of only 27 months [27]. On the other hand, Jennings et al reported a higher rate of complications (27.7%) and reoperations (20%) [34] This series involved a head-liner exchange without revising the cup, as the implant was modular, and they had the choice of retaining the cup if they believed it was stable. In addition, their study had a mean follow-up of only 15 months.

In our study, we revised the cup even though retention of the cup and conversion to a DM implant has been proposed in several studies [30,36,39,43-45]. The reason behind such proposal is that revision of the acetabular shell for large monoblock MoM implants can be technically challenging, especially in a well-fixed acetabular component, and can lead to loss of bone stock and increased instability. In addition, retention of the cup decreases surgical time and intraoperative complications [39,45]. A study by Colacchio et al concluded that it is a safe and viable option to perform a limited revision surgery and convert a monoblock MoM THA to a DM construct without exchanging the acetabular shell [36]. They showed a lower complication and rerevision rate of just 6.9% for the

Table 5
Outcomes following revision surgery of failed MoM hip prosthesis.

Article	Hips revised (n)	Reasons for revision	Implant types revised[a] (n)	Mean follow-up postrevision (mo)	Major complication rate (n)	Rerevision %
Liddle et al. (2013) [28]	39	- synovitis - infection - impingement - Pseudotumor - Acetabular osteolysis - PPF - LAC	S&N BHR (21) **DePuy ASR (6)** Stryker (5) Biomet (2) Mitch (2) Zimmer (2) DePuy Pinnacle (1)	30	5.2% - Dislocation (1) - Recurrent pseudotumor (1)	5.1% (2/39)
Pritchett (2014) [30]	90	- Pain - Noise - Effusion - Instability	S&N BHR (35) Wright (32) **DePuy ASR (8)** Stryker (7) Biomet (4) Zimmer Durom (4)	61	4.4% - Infection - Metallosis - Acetabular fracture - LAC	3.3% (3/90)
Munro et al. (2014) [39]	32	- ALTR - Deep infection - LAC	Zimmer Durom (31) **DePuy ASR (1)**	25	38% - Dislocation - LAC - ALTR recurrence - NVI	19% (6/32)
Wyles et al. (2014) [31]	37	- LAC - ALTR - PPF - Impingement - Dislocation - Pain	Biomet (15) **DePuy ASR (4)** DePuy S-ROM (2) DePuy Pinnacle (1) Zimmer (1) Zimmer Durom (1) Wright (3) Not available (10)	33	8% - Infection (3)	8% (3/37)
Cip et al. (2015) [27]	30	- ARMD	**DePuy ASR**	27	10% - Infection	5% (1/20)
Stryker et al. (2015) [32]	114	- Metallosis - LAC - Infection - Pain - Malposition - instability - Impingement - PPF	Biomet **DePuy ASR** Zimmer Wright	14	20% - Infection (7) - LAC (7) - Dislocation (5) - Acetabular fracture (3)	16% (18/114)
Liow et al. (2016) [33]	102	- Pseudotumor	DePuy Pinnacle (47) **DePuy ASR (30)** Stryker (25)	30	14% - Dislocation (4) - Pseudotumor recurrence (3) - LAC (3) - Wound infection (2) - DVT (1) - Intraoperative bleeding (1)	7% (7/102)
Iqbal et al. (2017) [29]	105	- ARMD	**DePuy ASR (32)** DePuy Pinnacle (7) S&N (23) Stryker/S&N (22) Wright (13) S&N/Zimmer (4) Stryker/Zimmer (2) Stryker (1) Zimmer (1)	20	18% - Dislocation (8) - Infection (7) - Hematoma (2) - PPF (2) - DVT (1)	5.7% (6/105)
Jennings et al. (2019) [34]	54	- Mechanical symptoms - Pain - Elevated metal ions - osteolysis	DePuy Pinnacle	15	27.7% - Dislocation (12) - Infection (3)	20% (11/54)
Crawford et al. (2019) [35]	203	- ARMD - LAC - Infection - LFC - Dislocation - PPF - Malposition	Biomet (162) **DePuy ASR (13)** DePuy Pinnacle (10) Wright (7) Zimmer (6) S&N (3) DJO global (2)	50	14% - ARMD (7) - LAC (6) - LFC (1) - Dislocation (1) - Infection (1) - Others (12)	7.9% (16/203)
Borton et al. (2019) [37]	180	- ARMD - LAC - Infection - Pain - Dislocation - PPF	Biomet M2a-38 (160) Biomet M2a-Magnum (18)	66	36% - ARMD (38) - Dislocation (11) - LAC (5) - Infection (5) - Neuropraxia (5) - Instability (1)	6.7% (12/180)

Table 5 (*continued*)

Article	Hips revised (n)	Reasons for revision	Implant types revised[a] (n)	Mean follow-up postrevision (mo)	Major complication rate (n)	Rerevision %
Chen et al. (2020) [41]	206	- ARMD - LAC - Infection - Dislocation - PPF	Zimmer Biomet	96	40% - LAC (25) - Dislocation (25) - PPF (16) - Infection (7) - Unbearable pain (8)	10% (20/206)
Colacchio et al. (2020) [36]	143	- ALTR - Pain - PPF - LAC - Infection	Biomet M2a-Magnum S&N BHR Wright	47	17.4% - LAC (7) - Infection (7) - Dislocation (6) - PPF (4) - Instability (1)	13.9% (20/143)
Lin et al. (2021) [42]	157	- ARMD - LAC - Dislocation - PPF	Zimmer Biomet	120	16.5% - LAC (11) - Dislocation (9) - Infection (2) - Unbearable pain (4)	3.8% (6/157)

ALTR, adverse local tissue reaction; ARMD, adverse reaction to metal debris; C/ S&N, Corin/Smith and Nephew; DVT, deep vein thrombosis; LAC, loose acetabular component; LFC, loose femoral component; NVI, neurovascular injury; PPF, periprosthetic fracture; S&N, Smith and Nephew; S&N/Z, Smith and Nephew/Zimmer; S&N BHR, Smith and Nephew Birmingham hip resurfacing.

Bold text indicates the specific prosthesis we are concerned with in this manuscript.

[a] Implant manufacturers: Biomet Inc (Warsaw, IN), Cormet (Corin grp, Lincester, UK, distributed by Stryker Orthopaedics, Mahwah, NJ), DePuy Synthes (Warsaw, IN), DJO Global (Dallas, TX), Smith and Nephew (Memphis, TN), Wright Technology Inc (Arlington, TN), Zimmer Inc (Warsaw, IN).

limited DM revision procedure group (n = 29) vs 20% complication rate and 16% rerevision rate in the formal revision group (n = 114) at mean follow-up of 3.9 years [36]. Their results, however, were inconsistent with a review article published by Affatato et al that showed a high complication rate for this limited DM procedure reporting a complication rate of 10.77% in this group (n = 130) with a mean follow-up of 20 months [46]. This shows that the best surgical option for failed monoblock MoM cups is still a topic of debate. Even though the DM limited revision procedure could be an easy solution, the design of the DM cup and MoM implants is different and has not been mechanically tested; therefore, more studies with long-term outcomes are needed.

Adverse reactions to metal debris have been considered one of the etiologies that lead to failure of primary MoM THA. Studies have shown that an increase in metal ion concentration can cause both local and systemic effects, ultimately leading to bone resorption and soft tissue damage [39] which can compromise hip stability in revision surgeries [47] and may increase the risk of infection [48]. Implant type, component positioning and diameter of bearing surfaces influence the level of metal ions released [49]. However, data is still lacking when finding a correlation between ALTRs and serum Co/Cr levels during a revision surgery [50]. Jennings et al reported a 22% (12/54) dislocation rate at 1 year follow-up for MoM revision undergoing a modular (head-liner) exchange, and 66.7% (8/12) required rerevision surgeries [34]. In addition, higher median cobalt and chromium ion levels were seen in these patients compared to patients with no complications [34]. Similar results were also shown by Penrose et al in which a 16% dislocation rate was reported at 2 years of follow-up for patients undergoing isolated acetabular component revision for patients with MoM THA [51], however, they were not able to differentiate between an acetabular shell revision or head-liner exchange and did not include metal ion levels. On the other hand, the National Joint Registry for England and Wales [52] showed that in patients undergoing revision of MoM THA, a modular head-liner exchange had a dislocation/subluxation rate of 33% and was considered a risk factor when compared to hips undergoing an acetabular shell revision, but also that no correlation with metal ion levels was reported [52]. In our study, there were 3 complications postrevision of the acetabular components (shell and head-liner exchange). One

patient had elevated cobalt (3.9 ppb) and chromium (1.5 ppb) levels at final follow-up, whereas the other 2 patients had a normal metal ion concentration (Table 4). Due to the low complication rate, the correlation between complication rate and metal ion levels was not reported in this study.

Per the table of intraoperative finding (Table 2), some patients failed due to an adverse soft tissue reaction secondary to metal debris, while other patients failed due to lack of cup ingrowth. Postrevision, metal ions in most patients tended to return to normal or near normal (<8 ppb); however, a few patients had ion levels that remained elevated (Table 4). Some of these patients had another joint replacement, which can explain the persistently elevated ion levels, while some patients did not.

We had fewer complication rates compared to other studies. This could be due to the standardized approach for evaluating patients preoperatively, a standardized surgical technique, and postoperative regimen. Also, none of our patients had any acetabular defects or wear. The soft tissue repair may have contributed to the decrease in dislocation rate. Furthermore, 2 studies have shown that large femoral head size between 36-40 mm decrease the risk of dislocation in revision THA [53,54]. In our study, the median postrevision head size was 36 mm, which further increased stability and decreased our postoperative dislocation rate. All our patients had a ceramic on polyethylene articulation, which can decrease the rate of infection [55] and aseptic loosening [56].

The main limitation of our study is the small number of cases. This limits our ability to discover clinical or demographic factors associated with complications after revision. Strengths of our study include 100% follow-up rate in our 24 revisions with average of 10 years of follow-up. In addition, all index THAs and revision surgeries were performed by a single surgeon at our institution, and the same implant manufacturer was used. Even though a single center and single surgeon study is not as powerful as a multicenter study, the outcomes of revision surgeries for THA depend highly on the surgeon's experience. Our study removed the variables that can affect the outcomes of revision surgeries by recording the outcomes of just one surgeon who used the same approach, technique, and revision implant for all his revision surgeries, which allowed consistency and predictability in hip components, surgical technique, and postoperative management. Most previously reported

revisions of MoM THAs are from multiple surgeons with different levels of experience, different surgical approaches, and the use of a variety of revision implants with which surgeons might not be familiar, leading to greater variability in the outcome and complication rates.

Conclusions

Our series shows significant functional improvement, as evidenced by increase in HHS and significant decreases in cobalt and chromium levels after revision surgery. Serum cobalt and chromium levels have been followed and reached acceptable levels in all cases. There were no failures or rerevisions for any reason including infection. We also demonstrate minimal acetabular bone loss following revision, as shown by median increase in cup size of only 6 mm. Our survival rate of revision at mean follow-up of 10 years is 100%. While MoM hips have required relatively high rates of revision surgery, our series shows the ability for patients to regain good function with high survivorship after revision.

Conflicts of interest

The senior author received research support from Depuy Synthes however it was not related to this study.

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