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Revision for Adverse Local Tissue Reaction Following Metal-on-Polyethylene Total Hip Arthroplasty is Associated with a High Risk of Early Major Complications

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The study design was conceived and developed by HBW and CPD. Data collection was performed by HBW. All authors contributed to the analysis and interpretation of the data. HBW, MRW and CPD drafted the manuscript. The final manuscript was edited and approved by all authors.

Aims: Fretting and corrosion at the modular head/neck junction, known as trunnionosis, in total hip arthroplasty (THA) is a recognized cause of adverse reaction to metal debris (ARMD). We describe the outcome of revision of metal-on-polyethylene (MoP) THA for ARMD secondary to trunnionosis with emphasis on the risk of major complication.

Patients and Methods: 36 patients with a MoP THR who underwent revision for ARMD due to trunnionosis were identified. Three patients were excluded due to revision to another metal head., the remaining 33 were revised to a ceramic head with a titanium sleeve. We describe the presentation, revision findings and risk of complications.

Results: Patients presented with pain, swelling, stiffness or instability and had an inflammatory mass confirmed radiologically. Macroscopic material deposition on the trunnion was seen in all cases, associated with ARMD. Following revision 6/33 dislocated, four of which required further revision. 3/33 developed post-operative infection. 6/33 reported significant on-going pain without obvious cause. One developed a femoral artery thrombosis after iliofemoral pseudotumor excision, requiring a thrombectomy.

Conclusions: The risk of serious complication following revision for ARMD secondary to trunnionosis is high. In the presence of extensive tissue damage, a constrained liner or dual mobility construct is recommended.

Clinical Relevance:

- The risk of major complications is high when revision for ARMD secondary to trunnionosis in MoP THA is performed.
- Dislocation and periprosthetic infection are the most common reasons for re-revision.

Introduction

The association between adverse reaction to metal debris (ARMD) or pseudotumours and metal-on-metal (MoM) total hip arthroplasty is well established.[1,2] Similar reactions occur in modular metal-on-polyethylene (MoP) total hip arthroplasties (THA),[3-6] although less frequently than in MoM resurfacing and THA.[7] This is not a new entity; corrosion at the head/neck junction[8] and pseudotumour in non-MoM THA was described in case reports three decades ago.[9] It is not limited to THA with revision for ARMD reported in modular hemiarthroplasty.[10] Analysis of head/neck taper junctions shows that material loss is predominantly from the head female taper,[11] and is caused by a combination of corrosion and mechanical wear or fretting,[12-14] collectively these mechanisms are termed trunnionosis.[13] Trunnionosis is a multifactorial problem[12] and the soft tissue damage caused by this pathology leads to an increased risk of complications.[15]

Fretting and corrosion have been associated with head/neck junction modularity and has been reported to occur in >30% of mixed-alloy head/stem combinations, in <10% of all-titanium-alloy modular components, and in <6% of all-cobalt alloy explanted devices.[16] Risk factors for the development of trunnionosis that have been proposed include high body mass index,[17] large-diameter femoral heads,[7,11,18] and trunnion design,[19,20] with shorter and thinner trunnions adopted to allow compatibility with ceramic heads and to increase impingement-free range-of-motion at greater risk.

Revision arthroplasty in the setting of AMRD on MoM hip arthroplasty is challenging and major complication rates as high as 38% and dislocation rates as high as 28% have been reported.[21] There is a paucity of evidence available on the complications associated with revision surgery for ARMD secondary to trunnionosis in MoP THA. The purpose of this report is to describe our experience of the treatment of patients with this condition and to emphasize the post-revision complication rate.

Patients and Methods

Approval was obtained from our institutional review board prior to the study. Thirty-six patients who underwent revision THA for ARMD secondary to trunnionosis in MoP THA, the diagnosis being confirmed by tissue samples sent to pathology at the time of the surgery,[3] were reviewed. All of the index primary THAs were performed between July 2005 and March 2013; 32 were performed at our institution and four at other centres. Between July 2005 and March 2013, 4581 primary MoP THAs were performed at our institution giving a prevalence of revision for ARMD secondary to trunnionosis of 0.7%. All revision THAs were undertaken between November 2011 and February 2017. During this time frame, 1000 revision THAs were performed in 819 patients at our institution, therefore revision of ARMD secondary to trunnionosis in MoP THA represented 3.6% of our revision burden. All revision procedures were performed at our institution by one of four surgeons. Three cases were excluded from analysis as they were revised to a further MoP bearing. This reflected our early practice, but this method was abandoned in favour of revision to a ceramic head with a titanium adaptor sleeve. ARMD recurrence occurred in two of the three excluded cases reinforcing this early change in practice.

The final study cohort (n=33) consisted of 21 females and 12 males, with a mean age of 66 years (range 38-89) and a mean BMI of 27 kg/m^2 (range 20-38).

The diagnosis prior to the primary THA was primary osteoarthritis in 24 patients, congenital dysplasia of the hip (CDH) in six, protrusio in two and avascular necrosis in one patient. Thirty-two of the primary THAs were performed through the posterior and one through a direct lateral approach. This reflects the predominant approach used in our unit during the period of the study. The demographic and primary surgical data is illustrated in Table 1. Of the femoral components, 26 were the Zimmer M/L Taper (Zimmer, Warsaw, Indiana, USA), two were DePuy Prodigy (DePuy, Warshaw, Indiana, USA), one was a Zimmer Wagner cone, one was a Zimmer Versys Beaded FullCoat, one was a Zimmer Anatomic, one was a DePuy Tri-lock and one was a Stryker Accolade (Stryker, Kalamazoo, Michigan, USA). This reflects the predominant choices of stem in our unit and region during the period of the study. Cobalt-chromium alloy heads were used in all primary cases. Thirty of the patients had a titanium/cobalt-chromium alloy trunnion head interface and three had a cobalt-chromium/cobalt-

chromium alloy interface. The bearing surface was highly cross-linked polyethylene in all 33 cases: Zimmer Longevity in 29; DePuy Altrx Pinnacle in three; and a Stryker Trident X3 in one. The acetabular components were modular, cementless titanium cups. The head sizes were 28mm in two cases, 32mm in 16, and 36 mm in 15.

The presenting symptoms prior to revision were pain alone in 18 patients, instability in nine patients, swelling in three patients and stiffness in the remaining three patients. All patients had a routine infection work up including a C-Reactive protein (CRP) and White Cell Count (WCC). If the CRP was elevated (>10 mg/dL) a joint aspirate with extended 14 day bacterial cultures was performed. All pre-operative extended cultures were negative for bacteria. Intraoperative tissue biopsies were obtained at the time of revision surgery in all patients and sent to microbiology and pathology for analysis. All intraoperative microbiology samples were negative after extended culture. All intraoperative pathology samples confirmed the presence of necrotic granulomatous tissue consistent with ARMD as per our previously described methods.[3]

All patients had radiographs on presentation. Twenty-six of the patients had further imaging (ultrasound (USS), computerized tomography (CT) or magnetic resonance imaging (MRI) scan). Based on clinical history, examination and investigations, the provisional diagnosis prior to revision surgery was: ARMD in 26 patients, instability in four patients, acetabular loosening in two patients, acetabular wall fracture in one patient. The seven cases where ARMD was not diagnosed prior to surgery did not have imaging performed beyond plain radiographs. All of the available pre-operative USS were reviewed by a radiologist and the lesions were classified according to Hauptfleisch.[22] Type I are thin-walled cystic masses (cyst wall <3 mm), Type II are thick-walled cystic masses (cyst wall >3 mm, but less than the diameter of the cystic component) and Type III are predominantly solid masses. Pre-operative radiographs were reviewed and graded according to Paprosky classification.[23]

Patients underwent revision a mean of 3.8 years after primary THA (range 1.3-9.0). Thirty-two of the revisions were performed through the posterior approach. One was performed through a combined iliofemoral and Smith-Peterson approach, necessitated by the size and location of the extensive pseudotumour. The hip was dislocated, the femoral head removed and the head and trunnion inspected for evidence of trunnionosis. In every case macroscopic evidence was reported, with thick black debris

deposited on the trunnion (Fig. 1). The trunnion was cleaned, inspected to confirm that there was no macroscopic damage, allowing the stem to be retained, and the femoral stem-bone interface inspected and loaded to ensure there was no stem loosening. In all cases the femoral head was replaced with a ceramic head with a titanium sleeve; 28mm heads were used in five cases, 32mm heads in seven cases, 36mm heads in 20 cases and a 40mm head in one case. The smaller heads were used when required in order to accommodate constrained acetabular liners when required. The primary acetabular shell was retained in 19 cases. Nine patients had the shell revised to a Zimmer Trabecular Metal shell, two patients had a revision to a Stryker Trident shell, two patients to a Stryker Anatomic Dual Mobility and one to a Zimmer Continuum shell. The acetabular liners were revised in all cases (Table II). Satisfactory acetabular orientation and impingement free range of motion were confirmed in all cases. A degree of increased constraint was used in 22 of the revision liners.

Statistical analysis

Statistical analyses were performed using GraphPad InStat (version 3.10, GraphPad Software, San Diego, California, USA). Multiple regression and correlation analyses were performed. The dependent variables were the type of complication and whether re-revision was required, the independent variables were the location of the ARMD lesion, the size of the lesion, the type of lesion, time to revision and the mode of presentation. Multicolinearity was assessed with R^2 values, the R^2 was less than 0.75 for each variable and therefore no variables were excluded from the model. A p-value <0.05 was considered to be significant.

Results

Osteolysis (Paprosky type 1) was observed in eight cases and cup loosening in two cases. In the remaining 23 cases, no acetabular osteolysis or loosening was observed.

The ultrasound scans (n=22) were reviewed and the pseudotumours classified into three groups. Twelve of the lesions were type III, five were type II, four were a combination of type III and II and one was a type 1.

The multiple regression analysis revealed that the location of the ARMD lesion, the size of the lesion, the type of lesion, time to revision and the mode of presentation did not predict the type of complication (p=0.413) nor whether re-revision was required (p=0.331). The independent variables were poorly correlated with the type of complication (location of the ARMD lesion, -0.091; size of the ARMD lesion, -0.137; type of lesion, -0.180; time to revision, -0.346; mode of presentation, -0.319).

Pre-operative metal ion levels were measured in nine patients and all were raised. The mean cobalt level was 6.2ug/l (range 3.2-10.5). The mean pre-operative chromium level was 1.5ug/l (range 0.1-3.2).

The mean follow up after revision surgery was 3.2 years (range 0.8-6.0). Six patients went on to have instability following revision surgery. Three of these patients had initially presented with instability following their primary THA. Four of the six underwent a second revision to a more constrained construct. The remaining two already had an elevated liner and it was elected to treat them conservatively.

Three patients became infected following revision; all of whom had a negative pre-operative workup for infection, no bacterial growth and no histological evidence of infection from intraoperative biopsies. One was treated with debridement and implant retention with modular exchange and six weeks of intravenous antibiotics. Staphylococcus lugdunensis was cultured from the debridement specimens. The patient was infection free at three years follow up. The second case was due to Methicillin Resistant Staphylococcus Aureus. The infection was successfully controlled with a first stage Prostalac temporary antibiotic loaded arthroplasty. The second stage was deferred due to her medical co-morbidities and she died one year after the first stage surgery and before the second stage could be completed. The third case was managed by two stage revision with an interval Prostalac arthroplasty. Group G beta haemolytic streptococcus

was isolated from intra-operative samples. There was no evidence of infection at three years follow up. The presenting symptom in all three infected cases was instability.

One case developed an acute femoral arterial thrombosis following iliofemoral exposure and resection of a massive thigh and intrapelvic pseudotumour. It was promptly recognized in the recovery room and successfully managed with a femoral thrombectomy.

Discussion

We have demonstrated a high risk of complications following revision for ARMD in MoP THA. In our series of 33 cases, 16 patients experienced a major complication of which seven required further revision and one required a further procedure (thrombectomy) without revision. The type of complication and whether revision was required was not predicted by the location, size or type of the ARMD lesion, time to revision nor mode of presentation. Patients need to be appropriately counselled regarding the high risk of complication following revision for ARMD that occurs in MoP THA.

ARMD in MoP THA requiring revision surgery remains rare. Case series have previously reported a prevalence of 1.1% for mechanically assisted crevice corrosion,[24] which is consistent with the prevalence of 0.7% in our series for cases for whom the primary was performed in our unit. These rates are higher than those reported in national registry studies where rates of revision for ARMD in non-MoM THA has been found to be 0.032%.[7] It is possible that there are more patients in the population covered by registries that have this pathology but have not yet developed symptoms or the pathology has not yet been diagnosed. ARMD and high revision rates have been widely reported in MoM THA,[25,26] but the pathology and its consequences are less well described in MoP THA.[3,4,7,9,15,27] The risk of revision for ARMD in MoM hip replacements is substantially higher, reported to be 3.7% in comparison to the 0.032% for MoP THA.[7] The most common reason for revision in our series was dislocation, followed by periprosthetic infection. Both of these are recognised complications of revision in this context.[5,15]

The typical presentation of this condition poses a significant diagnostic challenge. Pain, stiffness, swelling and instability are all non-specific symptoms. In this series, the diagnosis of ARMD was only made preoperatively in 26 of the 33 cases. The remaining seven cases all had alternative explanations for their symptoms (four had a diagnosis of instability, two had radiographic evidence of acetabular cup loosening, and one had diagnosis of osteolysis and acetabular wall fracture). It was only during the revision that the trunnionosis and ARMD became evident.

Our index of suspicion for this pathology has increased over time and we have evolved a standardised pre-operative work up. Infection is always excluded with inflammatory blood markers, which if raised, are followed by an aspiration of joint fluid for culture, manual cell count and differential, as well as aerobic and anaerobic culture and sensitivity out to 14 days. Following exclusion of infection, an USS is obtained. If the USS demonstrates a soft tissue mass or is equivocal, blood samples are taken to measure metal ion levels. Further imaging in the form of MRI is then considered to assist with definition of location and extent of the lesion. This sequence is based on our evaluation of the accuracy of USS at our centre.[28]

The nine patients that initially presented with instability had a particularly high re-revision rate. Three of the cases of instability following revision had initially presented with instability following their index primary procedure. Out of those that presented with instability, all but one received a constrained or dual mobility liner at the first revision. The patient who did not, had an increase in head size from 36 + 0mm to 40 + 0mm but still went on to experience further instability requiring revision to a constrained liner. One patient still had instability despite the use of a dual mobility liner at the first revision. Given the significant complications experienced in the patients that presented with instability in the context of ARMD, a high level of constraint should be considered in this subgroup.

All three of the patients who went on to develop post-revision periprosthetic infections initially presented with instability. The infection rate following MoM revision surgery has previously been reported as higher than that of revision surgery for MoP aseptic loosening; 8.1%[29] versus 3.2%.[30] Our infection rate of 9% is high and is more in keeping with the infection rate following MoM revision. Although we were unable to establish a statistical correlation between the size, location and type of lesion with presenting symptoms, presentation of ARMD with instability does appear to be a particularly high risk group in terms of this complication. This is reflective of the severity of the soft tissue damage due to the ARMD. The predominance of one stem type is reflective of our practice and that of surrounding units at primary surgery. The gender distribution is typical for patients undergoing primary THA and those undergoing revision for ARMD.[7]

This report has strengths and limitations. We report the prevalence of revision for this pathology on a large series of consecutive primary THAs from a tertiary joint replacement unit. Comprehensive records of primary and revision procedures allows us to capture all revision episodes performed and histological confirmation of the pathology. Whilst we acknowledge that it is possible revision of primaries performed in our unit may have been carried out elsewhere, this is very unlikely for patients that remain resident in our unit's region due to the nature of the healthcare system and referral processes. This is the largest series of revisions due to ARMD in MoP THA reported to date. As this is a single centre cohort series, there is the possibility of bias, particularly over time and, as we have reported, our index of suspicion for this pathology has increased over time. Our revision strategy has also evolved, hence we excluded three early cases where revision to another MoP bearing were performed as the outcomes of this strategy would not be generalisable to this cohort where revision to ceramic heads with a titanium sleeve were performed. Interestingly, ARMD recurred in two out of the three excluded cases. We believe that by changing the cobalt-chrome head on a titanium stem to one with a titanium sleeve and ceramic head, the source of the cobalt and chromium ions has been removed, preventing recurrence.

In conclusion, trunnionosis at the modular interface of the trunnion and the femoral head, that is likely to arise from material loss from the female taper of the head, in MoP THAs is a potential source of implant failure. This phenomenon appears to be particularly prevalent, but not exclusively, when the articulation is between differing alloys.[12] In our case series, by changing the material of the interface between the head and neck to match the alloy of the trunnion, we have not seen any recurrence of ARMD to date. Presentation of instability in the context of ARMD appears to have a particularly high morbidity and patients should be counselled accordingly.

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Table I. Primary THA components

Case	Femoral component	Original liner	Interface	Head size	Acetabulum Component
1	Strker Accolade 127 V40	Trident X3	Ti/CoCr	28 + 8	Stryker Trident
2	Zimmer ML Taper stem st	Longevity	Ti/CoCr	36 - 3.5	Zimmer Trilogy
3	Zimmer ML Taper St	Longevity	Ti/CoCr	32 + 0	Zimmer Trilogy
4	Zimmer ML Taper St	Longevity	Ti/CoCr	32 + 0	Zimmer Trilogy
5	Zimmer ML Taper St	Longevity	Ti/CoCr	36 + 0	Zimmer Trilogy
6	Zimmer ML Taper St	Longevity	Ti/CoCr	32 + 0	Zimmer Trilogy
7	Zimmer ML Taper Hi	Longevity	Ti/CoCr	36 + 0	Zimmer Trilogy
8	Zimmer ML Taper Hi	Longevity	Ti/CoCr	28 + 0	Zimmer Trilogy
9	Zimmer ML Taper St	Longevity	Ti/CoCr	32 + 0	Zimmer Trilogy
10	Zimmer ML Taper St	Longevity	Ti/CoCr	32 + 0	Zimmer Trilogy
11	Zimmer ML Taper Hi	Longevity	Ti/CoCr	32 + 0	Zimmer Trilogy
12	Zimmer ML Taper St	Longevity	Ti/CoCr	32 + 0	Zimmer Trilogy
13	Zimmer ML Taper St	Longevity	Ti/CoCr	36 + 3.5	Zimmer Trilogy
14	Zimmer ML Taper Hi	Longevity	Ti/CoCr	36+0	Zimmer Trilogy
15	Zimmer ML Taper St	Longevity	Ti/CoCr	32 + 0	Zimmer Trilogy
16	Zimmer ML Taper St	Longevity	Ti/CoCr	36 - 3.5	Zimmer Trilogy
17	Zimmer ML Taper Hi	Longevity	Ti/CoCr	36 + 0	Zimmer Trilogy
18	Zimmer VerSys Beaded Fullcoat	Longevity	CoCr/CoCr	36 - 3.5	Zimmer Trilogy
19	Zimmer Wagner cone	Longevity	Ti/CoCr	32 + 3.5	Zimmer Trilogy
20	Zimmer ML Taper St	Longevity	Ti/CoCr	36 + 0	Zimmer Trilogy
21	Zimmer ML Taper Hi	Longevity	Ti/CoCr	32 + 3.5	Zimmer Trilogy
22	Zimmer ML Taper St	Longevity	Ti/CoCr	36 + 0	Zimmer Trilogy
23	Zimmer ML Taper St	Longevity	Ti/CoCr	36 + 3.5	Zimmer Trilogy
24	Zimmer ML Taper Hi	Longevity	Ti/CoCr	36 + 3.5	Zimmer Trilogy
25	Zimmer ML Taper St	Longevity	Ti/CoCr	32 + 0	Zimmer Trilogy
26	Zimmer ML Taper St	Longevity	Ti/CoCr	36 -3.5	Zimmer Trilogy
27	Zimmer ML Taper Hi	Longevity	Ti/CoCr	32 + 0	Zimmer Trilogy
28	Zimmer ML Taper St	Longevity	Ti/CoCr	36 + 0	Zimmer Trilogy
29	Depuy Tri-lock	Altrx Pinnacle	Ti/CoCr	32 + 9	Depuy Pinnacle
30	Zimmer Anatomic	Longevity	Ti/CoCr	32 + 7	Zimmer Trilogy
31	Depuy Prodigy	Altrx Pinnacle	CoCr/CoCr	32 + 0	Depuy Pinnacle
32	Zimmer ML Taper St	Longevity	Ti/CoCr	32 + 0	Zimmer Trilogy
33	Depuy Prodigy	Altrx Pinnacle	CoCr/CoCr	36 + 5	Depuy Pinnacle

Table II. Revision THA components

Case	Presentation	Revision liner	Revision shell	Revision head size	Revision head
1	Instability	Stryker ADM	Stryker ADM	28 + 8	Ceramic with Ti sleeve
2	Instability	Zimmer TLC	Retained Zimmer Trilogy	32 + 3.5	Ceramic with Ti sleeve
3	Instability	Zimmer TLC	Retained Zimmer Trilogy	28 + 0	Ceramic with Ti sleeve
4	Difficulty with flexion	Zimmer TLC	Zimmer Continuum	32 + 3.5	Ceramic with Ti sleeve
5	Groin pain	Zimmer Longevity increased offset	Zimmer TM	36 + 7	Ceramic with Ti sleeve
6	Anterior swelling	Zimmer Longevity	Retained Zimmer Trilogy	36 + 3.5	Ceramic with Ti sleeve
7	Instability	Zimmer TLC	Retained Zimmer Trilogy	36 + 0	Ceramic with Ti sleeve
8	Groin pain	Stryker Trident	Stryker Trident	36 + 0	Ceramic with Ti sleeve
9	Groin swelling	Zimmer TLC	Retained Zimmer Trilogy	28 + 0	Ceramic with Ti sleeve
10	Instability	Stryker ADM	Retained Stryker ADM	28 + 3.5	Ceramic with Ti sleeve
11	Stiffness	Zimmer Longevity increased offest	Retained Zimmer Trilogy	36 + 0	Ceramic with Ti sleeve
12	Groin pain	Zimmr Longevity	Retained Zimmer Trilogy	32 + 0	Ceramic with Ti sleeve
13	Fibrous non-union	Zimmer Longevity	Zimmer TM	36 + 7	Ceramic with Ti sleeve
14	Instability	Zimmer Longevity	Retained Zimmer Trilogy	40 + 0	Ceramic with Ti sleeve
15	Instability	Zimmer Longevity elevated rim	Zimmer TM	32 + 7	Ceramic with Ti sleeve
16	Instability	Zimmer TLC	Retained Zimmer Trilogy	32 + 3.5	Ceramic with Ti sleeve
17	Stiffness and groin pain	Zimmer Longevity elevated rim	Retained Zimmer Trilogy	36 + 3.5	Ceramic with Ti sleeve
18	Groin pain	Zimmer Longevity	Retained Zimmer Trilogy	36 - 3.5	Ceramic with Ti sleeve
19	Presumed acetabular loosening	Zimmer Longevity	Zimmer TM	36 + 3.5	Ceramic with Ti sleeve
20	Lateral hip pain	Zimmer Longevity elevated rim	Retained Zimmer Trilogy	36 + 3.5	Ceramic with Ti sleeve
21	Anterior and lateral pain	Stryker Trident eleveted rim	Retained Styker Trident	36 + 7	Ceramic with Ti sleeve
22	Posterior hip pain	Zimmer Longevity	Retained Zimmer Trilogy	36 + 3.5	Ceramic with Ti sleeve
23	Anterior swelling	Zimmer TLC	Zimmer TM	36 + 3.5	Ceramic with Ti sleeve
24	Groin pain	Zimmer Oblique TM liner	Zimmer TM	36 + 0	Ceramic with Ti sleeve
25	Groin pain	Zimmer Longevity elevated rim	Retained Zimmer Trilogy	32 + 3.5	Ceramic with Ti sleeve
26	Diffuse pain	Zimmer Longevity	Retained Zimmer Trilogy	36 + 0	Ceramic with Ti sleeve
27	Groin pain	Zimmer TLC	Retained Zimmer Trilogy	28 + 0	Ceramic with Ti sleeve
28	Groin pain	Zimmer Longevity oblique mouth	Retained Zimmer Trilogy	36 + 3.5	Ceramic with Ti sleeve
29	Groin pain	Depuy Pinnacle	Retained Depuy Pinnacle	36 + 12	Ceramic with Ti sleeve
30	Instability	Zimmer Longevity elevated rim	Zimmer TM	32 - 3.5	Ceramic with Ti sleeve
31	Groin pain	Depuy Pinnacle	Retained Depuy Pinnacle	36 + 5	Ceramic with Ti sleeve
32	Lateral hip pain	Zimmer TLC	Zimmer TM	36 + 3.5	Ceramic with Ti sleeve
33	Anterior swelling	Zimmer TLC	Zimmer TM	36 + 0	Ceramic with Ti sleeve

Figure legends

Figure 1. Macroscopic evidence of material deposition on the trunnion with thick black debris visible