International Orthopaedics (SICOT) (2017) 41:1101–1105
DOI 10.1007/s00264-016-3314-0

ORIGINAL PAPER

Retrieval analysis of ceramic-coated metal-on-polyethylene total hip replacements

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Received: 8 August 2016 / Accepted: 10 October 2016 / Published online: 25 October 2016

Abstract
Purpose Ceramic coatings have been used in metal-on-polyethylene (MOP) hips to reduce the risk of wear and also infection; the clinical efficacy of this remains unclear. This retrieval study sought to better understand the performance of coated bearing surfaces.
Methods Forty-three coated MOP components were analysed post-retrieval for evidence of coating loss and gross polyethylene wear. Coating loss was graded using a visual semi-quantitative protocol. Evidence of gross polyethylene wear was determined by radiographic analysis and visual inspection of the retrieved implants.
Results All components with gross polyethylene wear (n = 10) were revised due to a malfunctioning acetabular component; 35 % (n = 15) of implants exhibited visible coating loss and the incidence of polyethylene wear in samples with coating loss was 54 %, significantly (p = 0.02) elevated compared to samples with intact coatings (14 %).
Conclusions In this study we found evidence of coating loss on metal femoral heads which was associated with increased wear of the corresponding polyethylene acetabular cups.

Keywords Wear · Coating · Metal-on-polyethylene · Retrieval · Hip

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Background

Conventional metal-on-polyethylene (MOP) total hip replacements (THRs) are susceptible to wear of the polyethylene bearing, which may be associated with osteolysis and aseptic loosening [1]. The use of titanium-nitride (TiN) or titanium-niobium-nitride (TiNbN) based coatings on the metal femoral head [2] offers theoretical advantages of minimising polyethylene wear [3, 4].

In vitro mechanical hip simulation of coated MOP bearings under standard and adverse conditions has demonstrated a reduction in wear [4–6]. However, recent retrieval studies have demonstrated that simulation does not always predict real life [3, 7–10], although these have investigated small numbers of implants.

It is reported that when coating breakthrough occurs in TiN coated components, the wear properties of the implant revert to that of a typical un-coated prostheses and the polyethylene wear rate increases [11–14]. The frequency and severity of coating removal in a larger cohort of implants is however unknown and the effect of this on risk of revision is not fully understood.

In this study we sought to: (1) characterise the location, incidence and severity of coating loss in a series of 43 retrieved, coated MOP hips, (2) identify components with gross polyethylene wear and (3) determine if there was a correlation between coating loss and polyethylene wear.

Methods

This retrieval study involved a series of 43 coated MOP THRs that were consecutively collected from a single revising institution and subsequently sent to our centre for analysis; the femoral heads had been coated with either

TiN (n = 39) or TiNbN (n = 4). The hips were retrieved from 19 male and 24 female patients with a median age of 73 (27 – 88) years at primary surgery and a median time to revision of 73 (11 – 193) months; the heads were 36 mm in diameter. The reasons for revision, as reported by the revising surgeon, were loosening of cup and stem (n = 5), loosening of cup (n = 9), loosening of stem (n = 7), infection (n = 5), metallosis (n = 3), dislocation (n = 1) and gross cup damage (n = 10); the reason for revision could not be identified in three cases.

Characterising coating removal

A semi-quantitative visual grading protocol was implemented for analysing coating removal; this protocol was adapted for use in this study from previously published work describing the detailed inspection of hip implant bearing surfaces [15]. The surface of each femoral head was visually divided into eight zones (Fig. 1), and each zone was scored on a scale of 0–3 based on the extent of coating removal exhibited in that area (Table 1). The scores for each zone were totalled, providing an overall 'coating-loss' score for each implant. Examinations were performed independently by two examiners experienced in retrieval analysis. This methodology facilitated analysis of coating loss with regards to (1) incidence, (2) severity and (3) location.

Scanning electron microscopy

We used a JEOL JSM (Tokyo, Japan) scanning electron microscopy (SEM) with secondary electron detection at an accelerating voltage of 20 KV to examine surface differences between coated surface regions and regions where coating loss had occurred.

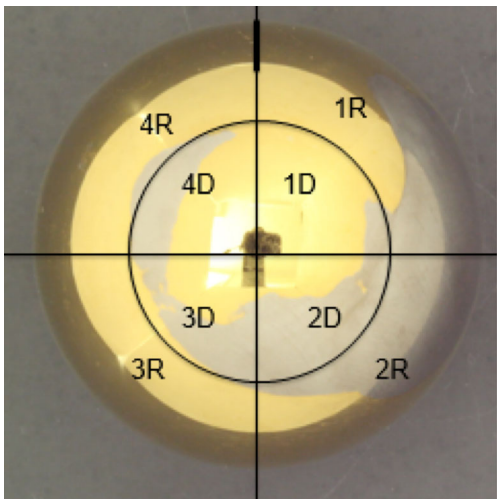

Fig. 1 The surface of the component was divided into eight nominal zones, four in the polar region of the implant head (1D, 2D, 3D, 4D) and four in the equatorial region of the implant head (1R, 2R, 3R, 4R)

Table 1 Description of the extent of coating removal for each zone and the associated score

Proportion of surface area with coating loss	Score
No coating loss	0
0-25 %	1
25-75 %	2
75-100 %	3

Assessment of polyethylene wear

Pre-revision plain radiographs were available for 35/43 hips; these were analysed by an experienced orthopaedic surgeon for evidence of gross wear of the polyethylene acetabular component. An implant head positioned asymmetrically in the acetabular component was deemed to have mechanically worn the polyethylene cup [16–18]. Gross polyethylene wear was characterised if the X-ray demonstrated implant head penetration in a supero-lateral direction [17, 19–21]. The retrieved polyethylene cups' bearing surfaces were also macroscopically examined by a single observer for evidence of adhesive and third body abrasive wear. In all cases, the result of analysis was either (1) clear evidence of polyethylene wear or (2) no clear evidence of polyethylene wear.

Statistical analysis

The strength of agreement in the coating-loss scores reported by the two examiners was assessed by performing Cohen's weighted Kappa (κ) statistical analysis; Kappa values were assessed using the assessment criteria of $\kappa \leq 0$ = poor, 0.01–0.20 = slight, 0.21–0.40 = fair, 0.41–0.60 = moderate, 0.61–0.80 = substantial, 0.81–1 = almost perfect.

Non-parametric tests were performed to test the strength of correlations between coating loss and polyethylene wear.

Results

Characterising coating removal

We found that 35 % (n = 15) of femoral heads exhibited some evidence of coating removal whilst the coatings appeared to have remained intact in 65 % (n = 28) of cases. In cases with coating removal, the median (range) score for severity of loss was 4 (1–10), out of a maximum of 24. The polar regions (D zones) had significantly greater coating loss than the equatorial regions (R zones) ($p < 0.01$).

Scanning electron microscopy

Examination of the head surfaces under SEM revealed considerable evidence of scratching on the exposed metal

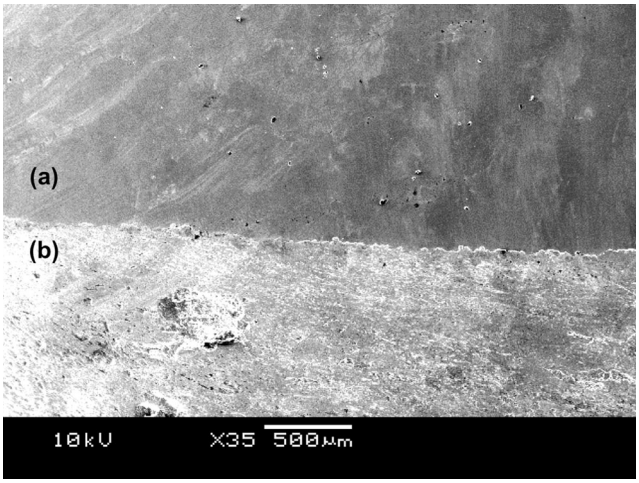

Fig. 2 SEM analysis revealed (**a**) minimal scratching on the coated surface regions and (**b**) considerable scratching of the exposed surfaces with coating loss

surfaces, possibly due to third bodies such as coating fragments (Fig. 2). There were small localised regions of coating loss visible in the coated areas however there was notably less evidence of scratching.

Assessment of polyethylene wear

Of the 35 cases available for radiographic analysis, 37 % (n = 13) revealed evidence of gross polyethylene wear (Fig. 3). All implants that were categorised as

Fig. 3 Gross polyethylene wear was characterised if the X-ray demonstrated implant head penetration in a supero-lateral direction

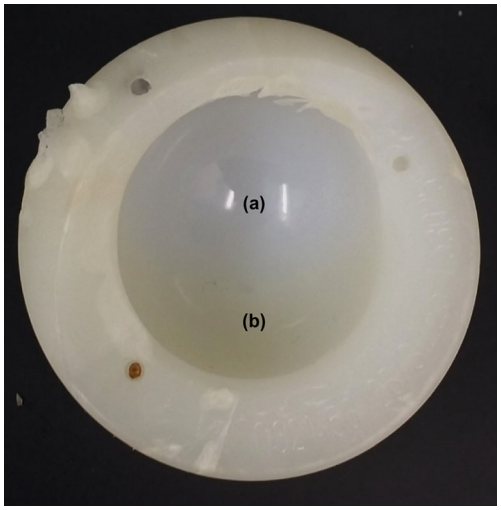

Fig. 4 Inspection of the polyethylene components revealed regions with (**a**) glossy surfaces and (**b**) dull appearance to the surface

demonstrating polyethylene wear upon radiographic analysis were revised due to a malfunctioning acetabular component, either due to cup loosening or gross cup damage.

Upon visual inspection, distinctly dull areas of apparent wear were present on the surface of these components, indicative of abrasive wear (Fig. 4). These regions were adjacent to areas of glossy wear, indicative of adhesive wear.

Statistical analysis

Weighted kappa analysis comparing the scores between the two examiners yielded a value of 0.659; this suggested substantial agreement between the two examiners in assessment of coating loss.

The incidence of polyethylene wear in samples with coating loss was 54 %, which was significantly (p = 0.02) elevated compared to samples with intact coatings (14 %) (Fig. 5).

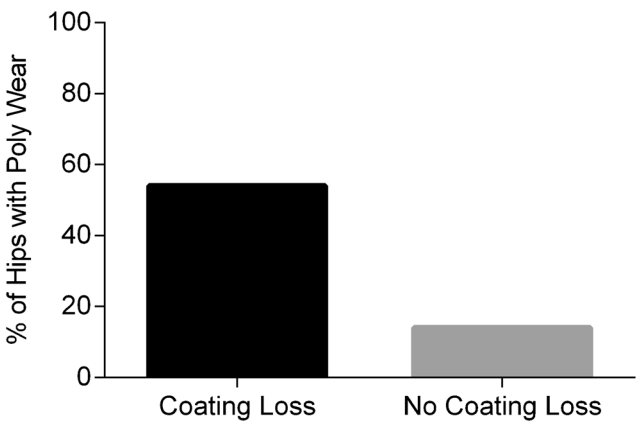

Fig. 5 Plot of the distribution of hips with gross poly wear with femoral heads exhibiting evidence of coating loss or no loss visible

Discussion

This study demonstrated that coating loss was visible in 35 % of samples and more common in the polar than equatorial region of the implant. Components with accompanying radiographs that exhibited gross polyethylene were revised due to a malfunctioning polyethylene component. These components exhibited adhesive and third-body abrasive wear upon visual inspection. We found a significant correlation between the incidence of coating loss and the incidence of gross polyethylene wear.

The existence of visible coating removal raises issues regarding the cause of detachment and the clinical viability of the prosthesis post-detachment *in vivo*. The propensity for coating failure may be related to a number of variables, such as the method of coating application, which dictates relative adhesion strength of the coating [2]. The method of adhesion used in the prostheses in this study was unknown. A possible explanation for coating removal centres on the principle that the presence of third body particles at the bearing surface may elicit a wear mechanism that leads to coating detachment. Entrapment of third body particles, such as titanium debris and PMMA cement, between the polyethylene and the femoral head component may have increased local stresses within the coating [3, 22]. This may lead to fracture propagation within the coating, thus leading to coating delamination [23, 24].

Coating removal may have led to increased polyethylene wear. The exposed metal substrate may have worn the polyethylene to a greater degree than the coated region, due to the increased surface roughness of the metal surface in comparison to the ceramic coating [25–27]. Another possible mechanism for increased polyethylene wear may be detached coating fragments manifesting as third body particles embedded in the articulating space between femoral head component and polyethylene.

The difference in the amount of coating loss in the polar and equatorial region may be due to differential loading of the regions due to geometric implant design features [28–30]. The work of Tudor et. al [31] demonstrated that relatively greater distances between articulating surfaces results in greater contact pressures on the polar region than the equatorial region. Conversely, relatively smaller distances between articulating surfaces have demonstrated greater contact pressure applied in the equatorial region of the implant than the polar region [31]. The differential contact pressures of the two areas could aid in explaining the difference in incidence of coating loss between polar and equatorial regions.

This study suggests there may be a possible association between coating loss and polyethylene wear, thus impacting the clinical performance of the prosthesis. However, this study did not fully examine all relevant surgical and patient factors. For example, surgical implantation technique data and patient related factors, such as body mass index and patient activity, were not available in the present study. Acquisition of this data in future studies may provide more information about the clinical outcome of these prostheses. Additionally, the nature of retrieval analysis is that all implants in this study had failed; it is not clear what the extent of coating loss is in well-functioning implants. It is also important to note that the extent of wear in contemporary highly cross-linked MOP hips has been favourable [32, 33]; this supports the approach of optimising the polyethylene material used rather than introducing coatings to reduce wear.

Conclusion

In this study we examined a consecutive series of retrieved, coated MOP hips and found evidence of coating loss which was associated with increased polyethylene wear. Future work will investigate which surgical, implant and patient factors increase the risk of coating loss occurring.

Acknowledgments We are grateful for the support of Gwynneth Lloyd, Elizabeth Ellis and Akramul Hoque for their coordination of the retrieval centre and the surgeons and patients that have contributed implants to this study.

Two authors received funding from the British Orthopaedic Association through an industry consortium of nine manufacturers: DePuy International Ltd, Zimmer GmbH, Smith & Nephew UK Ltd, Biomet UK Ltd, JRI Ltd, Finsbury Orthopaedics Ltd, Corin Group PLC, Mathys Orthopaedics Ltd, and Stryker UK Ltd.

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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