Risk of Impingement and Third-body Abrasion With 28-mm Metal-on-metal Bearings

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Abstract

Background Concerns have been raised about the sequelae of metal-on-metal (MoM) bearings in total hip arthroplasty (THA). However, retrieval studies, which offer the best insight into the clinically relevant mechanisms of MoM wear, have followed predictable trends to date such as indicting cobalt-chromium (CoCr) metallurgy, cup design, high conformity between the head and cup, “steep cups,” “microseparation,” and “edge wear.”

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Questions/purposes We wished to evaluate a set of retrieved 28-mm MoM THA for signs of (1) cup-to-stem impingement; (2) normal wear pattern and concomitant stripe damage on femoral heads that would signify adverse wear mechanics; and (3) well-defined evidence of third-body scratches on bearings that would indicate large abrasive particles had circulated the joint space.

Methods Ten 28-mm MOM retrievals were selected on the basis that femoral stems were included. Revision surgeries at 3 to 8 years were for pain, osteolysis, and cup loosening. CoCr stems and the MoM bearings were produced by one vendor and Ti6Al4V stems by a second vendor. All but two cases had been fixed with bone cement. We looked for patterns of normal wear and impingement signs on femoral necks and cup rims. We looked for adverse wear defined as stripe damage that was visually apparent on each bearing. Wear patterns were examined microscopically to determine the nature of abrasions and signs of metal transfer. Graphical models recreated femoral neck and cup designs to precisely correlate impingement sites on femoral necks to cup positions and head stripe patterns.

Results The evidence revealed that all CoCr cup liners had impinged on either anterior or posterior facets of femoral necks. Liner impingement at the most proximal neck notch

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occurred with the head well located and impingement at the distal notch occurred with the head rotated 5 mm out of the cup. The hip gained 20° motion by such a subluxation maneuver with this THA design. All heads had stripe wear, the basal and polar stripes coinciding with cup impingement sites. Analysis of stripe damage revealed 40 to 100-μm wide scratches created by large particles ploughing across bearing surfaces. The association of stripe wear with evidence of neck notching implicated impingement as the root cause, the outcome being the aggressive third-body wear.

Conclusions We found consistent evidence of impingement, abnormal stripe damage, and evidence of third-body abrasive wear in a small sample of one type of 28-mm MoM design. Impingement models demonstrated that 28-mm heads could lever 20° out of the liners. Although other studies continue to show good success with 28-mm MoM bearings, their use has been discontinued at La Pitie Hospital.

Level of Evidence Level IV, therapeutic study. See Guidelines for Authors for a complete description of levels of evidence.

Introduction

Contemporary metal-on-metal (MoM) THA offered perceived benefits of lower wear than polyethylene cups and with availability of larger diameter heads also added the benefits of improved ROM and stability [1, 81]. Both positive [2, 11] and negative reports [25, 34, 35, 37, 61] have emerged with regard to using MoM bearings. There are likely many risks that could trigger a need for MoM revision. Many studies focused on cobalt-chromium (CoCr) alloys, cup designs (Fig. 1), surgical positioning, and effects of “edge loading” [12, 23, 29, 38, 58, 59, 76]. Additionally, impingement, subluxation, and dislocation have always been unpredictable risk considerations [3, 18,

22, 24, 27, 28, 31, 43, 52, 66, 72, 74, 77, 80]. Aggressive third-body abrasive wear can be one result of THA impingement [10, 24, 26, 27, 50].

Retrieval studies of ceramic-on-ceramic (CoC) THA in particular have revealed “normal” wear mode produced by everyday activities as a circular wear pattern on the head and inside the cup [71, 75]. There were also frequent reports of “stripe” wear across heads and around cup rims [15, 54, 62, 71, 77]. Our MoM retrieval studies noted similar stripe damage in retrieved MoM [6, 9, 10], although other groups disavowed their existence [34]. Conventional MoM teaching is that the release of small surface carbides creates 0.5 to 5-μm wide scratches as a “self-polishing” mechanism [65, 69, 73]. Nevertheless, one MoM retrieval study noted the presence of 100-μm wide scratches. The authors proposed that large CoCr particles had been produced during impingement episodes and these created the large scratches [27].

Therefore, we selected from our inventory a set of 10 28-mm MoM bearings that included the femoral stems. We sought to document (1) signs of cup-to-stem impingement; (2) patterns of normal and adverse wear damage; and (3) evidence for third-body abrasion of the same magnitude as described in the McKee-Farrar study [27].

Materials and Methods

The index 28-mm MoM procedures were performed in a number of hospitals in France and followed in the Orthopaedic Department of La Pitie Saltpetriere Hospital (Paris, France) [41]. Ten MoM bearings with femoral stems were selected for study (Table 1). The seven anodized titanium-alloy stems were cemented (Alizé™, Fournitures Hospitalières, Quimper, France). In the three remaining stems (Sulzer Orthopedics, Winterthur, Switzerland), two were press-fit (Protasul-2 alloy) and one was a cemented iron-based

Fig. 1A–B This example of a second-generation 28-mm cup design [13, 78] illustrates (A) cup-bearing angle (CBA) and cup-face angle (CFA) as a function of rim heights H_b and H_f , respectively, where H =

overall height of cup; R = internal cup radius; r = radius at inner rim of cup. (B) SEM image of silicone cup replica shows the cross-section of the inner rim.

Table 1. Summary of metal-on-metal cases with reasons for revision

Patient number	Sex	Age (years)	Followup (years)	Reasons for revision	Stem type	Cup type	Operated side
1	F	59	6	Pain, osteolysis on CT	FHO (Ti6Al4V; cement)	Cem-PE	Right
2	F	56	5	Pain, swelling	FHO (Ti6Al4V; cement)	Cem-PE	Right
3	F	62	6	Pain, swelling, osteolysis	FHO (Ti6Al4V; cement)	MB	Right
4	F	60	5	Osteolysis, pain, subluxation	SULZER (Ti6Al6Nb; noncement)	MB	Left
5	F	47	3	Pain, osteolysis, late subluxation, swelling	SULZER (stainless steel; cement)	Cem-PE	Left
6	M	70	7	Pain, osteolysis on CT	FHO (Ti6Al4V; cement)	Cem-PE	Right
7	F	57	5	Pain, subluxation, swelling, osteolysis on CT	SULZER (CoCr; cement)	Cem-PE	Right
8	F	51	8	Pain, swelling, osteolysis on CT	FHO (Ti6Al4V; cement)	Cem-PE	Left
9	F	55	6	Pain, swelling, osteolysis on CT	FHO (Ti6Al4V; cement)	Cem-PE	Left
10	F	50	3	Pain, osteolysis on CT, secondary subluxation	SULZER (CoCr; cement)	Cem-PE	Left

F = female; M = male; FHO = FH-Orthopedics, Heimsbrunn, France; SULZER = Sulzer Orthopedics, Berne, Switzerland (now Zimmer, Warsaw, IN, USA); CoCr = cobalt-chromium; Cem-PE = cemented polyethylene cup; MB = metal-backed cup with cobalt-chromium liner in polyethylene adaptor.

Table 2. Hip imaging (EOS) while standing with reference to postural positions [40, 42]

Patient number	Incidence	Sacral slope	APP	Cup frontal	Cup sagittal	Cup AV	Neck frontal	Neck/cup axis	CPR
1	77	46	—	51	43	37	53	103	53
2	55	43	−7	55	59	32	54	115	43
3	80	48	−3	43	47	48	54	95	64
4	85	22	−3.5	39	29	68	54	79	79
5	60	47	4	42	40	45	55	93	67
6	82	42	−10	47	59	45	54	106	52
7	56	21	−20	60	63	39	54	111	47
8	63	62	15	39	22	19	55	92	66
9	69	53	13	36	34	43	55	92	68
10	60	31	1	38	45	42	50	88	68

Incidence = as viewed in the sagittal plane, the angle between two reference lines: (1) a line from the center of the femoral head to the middle of the sacral plateau; and (2) a line perpendicular to the S1 end plate; Sacral slope = an angle formed by a tangent line to the upper plate of S1 and the horizontal plane; APP = anterior pelvic plane inclination measured by the angle subtended between the vertical plane and a line tangent to the anterosuperior iliac spine and pubic symphysis [42]; Cup sagittal = as viewed in the sagittal plane, the angle between the inclined axis of the cup and the horizontal plane; AV = true cup anteversion; CPR = contact patch to rim distance [36].

alloy (Protasul S30). Eight cups were cemented and two cups were press-fit (Table 1). All cases had received approval by the local research ethics committee [41]. Standard radiography and EOSTM imaging were used to analyze likely sites of impingement (Orthopaedic Department, La Pitie Saltpetriere Hospital, Paris, France). All patients were imaged by conventional radiography and by a slot scanning, x-ray system (EOS[®]; Biospace, Paris, France) [17, 39, 41–43, 70]. Implant orientations and contact patch to rim distance (CPR) [36] data were incorporated in each image. Patient functional posture was assessed while the patient was sitting and standing. In one

case, squatting was added to simulate a novel patient activity. EOS data in the standing position showed cup lateral inclination ranged from 36° to 60° and cup anteversion ranged from 19° to 68° (Table 2).

Retrievals were logged into the Donaldson Arthritis Research Foundation (DARF) Center, scrubbed with a plastic sponge, and then given several ultrasonic cleaning steps, first with a standard detergent in distilled water and then with alcohol solution followed by air-drying [7]. The implants were inspected for impingement damage and the head:neck ratios calculated (Table 3). MoM geometries were assessed by contour measurement methods (CMM;

Table 3. Details of 28-mm heads, cups, femoral stems, and neck notches

Stem	Neck diameter (mm)	H/N ratio	Ball neck-length adjustment	Taper length (mm)	Taper details	Neck (CB or DN)	Cup details
HFO (Alizé™; Fournitures Hospitalières, Quimper, France)	12	2.3	4	14.8	Taper exposed 4 mm	Yes	Type B
HFO	12.5	2.2	4	10.2	Covered by head	Yes	Type A
HFO	12.5	2.2	0	10.5	Covered	Yes	Type A
Sulzer (Sulzer Orthopedics, Winterthur, Switzerland)	12.4	2.3	−4	13.1	Covered by head	Yes	Type A
Sulzer	12.8	2.2	8	13.0	Skirted ball	Yes	Type A
HFO	12	2.3	4	14.3	Taper exposed 4 mm	Yes	Type B
Sulzer	13.9	2	0	15.3	Taper exposed 1.2 mm	Yes	Type A
HFO	12.5	2.2	0	10.7	Covered by head	Yes	Type A
HFO	12	2.3	4	14.8	Taper exposed 4 mm	Yes, abraded	Type B
Sulzer	14	2	−4	15.1	Covered by head	Yes	Type A

H/N ratio = head:neck ratio; CB = cosmetic blemish; DN = distinct notch.

Table 4. Contour measurement (CMM) studies of 28-mm metal on metal

Patient number	Ball diameter (mm)	Cup diameter (mm)	Cup-ball mismatch (μm)	Ball form factor (μm)	Cup form factor (μm)	Form factor ratio (cup/head)
1	27.984	28.173	189	127	80	0.6
2	27.985	28.101	116	11	12	1.1
3	27.986	28.108	122	13	36	2.7
4	27.988	28.071	83	7	6	0.8
5	28.007	28.097	90	38	12	0.3
6	27.987	28.097	110	9	39	4.2
7	27.983	28.076	92	12	8	0.7
8	27.99	28.096	106	11	13	1.2
9	27.999	28.108	109	19	34	1.8
10	28.001	28.084	83	10	24	2.4
Average	27.991	28.101	110	26	27	1.6
SD	0.008	0.028	31	37	23	1.2

Legex-322; Mitotoyo, Michigan, IN, USA). Head-cup mismatch averaged 110 μm and bearing form factors averaged 26 μm (Table 4). There were two types of liner, one with a rim extension that presented a 191° cup-face angle (Fig. 1A: Type A) and one with a 205° cup-face angle (Type B).

MoM bearings were examined for sites and patterns of habitual wear created by patient flexion-extension and abduction-adduction activities [5, 9, 33, 56]. Bands of protein deposits were noted but not included for study [7]. Surface features were graded visually by a hand lens (×3 magnification) and by stereomicroscopy. Main-wear zone patterns were measured by included-angles for heads and by chord dimensions for cups (Fig. 2A). Liners with wear patterns extending up to the rim were assessed by rim-breakout arcs (Fig. 2B). Standard spherical equations

provided surface arcs and areas of wear patterns. Wear areas were normalized to the MoM hemispherical area (“Hemi% ratio”) to provide comparisons across varied diameters of MoM.

In the analysis of adverse wear, “stripe” sites were identified visually and by aid of stereomicroscopy. Heads were outlined in ink and photographed in four orthogonal views. The liners were photographed en-face front and back. To determine cup impingement sites, each femoral head was mounted onto the femoral stem with the main wear zone pattern located superiorly. The cup was then rotated on the head to find impingement sites with the femoral neck and photographs taken [7, 9].

To model cup impingement sites, the geometry of each femoral neck and cup was measured (Tables 3, 4).

Fig. 2A–C Assessment of wear patterns formed on MoM bearings showed (A) cup main-wear zone and nonwear zone. (B) Breakout wear pattern around cup rim (angle). (C) Head wear depicting main

wear zone pattern, three types of stripes (basal, equatorial, polar), and circumferential notching of the femoral neck.

Table 5. Damage to femoral necks and tapers

Patient number	Stem material	Notch site	Notch details	Notch location
1	Ti6Al4V	Trunnion	DN	Posterior
2	Ti6Al4V	Neck	DN	Anterior
3	Ti6Al4V	Neck	DN	Posterior
4	CoCr	Neck	Mild DN	Posterior
5	CoCr	Skirt of ball	DN	Anterior
6	CoCr	Trunnion	CB, PMMA	Posterior
7	CoCr	Neck	CB	Posterior
8	Ti6Al4V	Neck	CB	Anterior
9	Ti6Al4V	Neck	CB	Anterior
10	CoCr	Neck	CB, DN	Posterior and superior

CoCr = cobalt-chromium; DN = well-defined circumferential notch; CB = cosmetic blemish; PMMA = abrasion created by bone cement.

Micrometer measurements of internal liner geometry provided cup-face angles (CFA), cup-bearing angles (CBA), ROM, and polar-impingement angles (Fig. 1A) [9, 23]. Liners were replicated in silicon (Aquasil-LVTM; Densply, Milford, DE, USA) and the replicas sectioned for scanning electron microscopy (SEM) analysis (Fig. 1B). Cup and neck geometries were precisely modeled to compare impingement notches, arcs of motion, stripe wear, and cup positions (Canvas; ACD Systems, Seattle, WA, USA).

To analyze surface damage on femoral heads, we used SEM (MA 15; Zeiss, Cambridge, UK; magnifications $\times 100$ – 1000) and white-light interferometry (WLI; NewView-600, $\times 5$ and $\times 25$ lenses; Zygo, Tucson, AZ, USA). Areas of suspected metal transfer were imaged by energy dispersive spectroscopy (EDS; Bruker Inc, Berlin, Germany). The small cup geometry proved unsuitable for microscopic study. Statistical comparisons between groups were made using t-tests, Dunn's multiple comparison tests, and box plots for nonparametric data (Kruskal-Wallis

analysis of variance) using Canvas (ACD Systems, Seattle, WA, USA).

Results

Evidence of Cup-Stem Impingement

Evidence of stem impingement was observed as circumferentially oriented, notch damage to femoral necks, and exposed trunnions (Table 5). Placing the cup at neck impingement sites revealed that the liner rim located exactly on the femoral notch. Deep notches (DN) were evident in one CoCr neck, one skirted CoCr head, and three Ti6Al4V necks (Fig. 3A–B). Cement protruding from a cup face also created neck abrasion (Fig. 3C). Stem notches were posterior in six cases and anterior in four. The volume of metal debris removed from one notched trunnion (Fig. 3A) was estimated at 8 to 9 mm³ (Fig. 4).

Fig. 3A–C Circumferential notching on necks and trunnions was noted as (A) deep notch (DN) in Ti6Al4V trunnion; (B) deep notch in Ti6Al4V neck; (C) cosmetic blemish (CB) and cement abrasion (PMMA) of anodized coating on a Ti6Al4V femoral neck.

Fig. 4 SEM image depicting a femoral notch that was cut 2.9 mm wide and 1 mm deep by the liner rim habitually wearing on the Ti6Al4V surface (see Fig. 3A).

Fig. 5 The cup rim that had cut three notches into a CoCr neck (see Fig. 6) was uniformly contoured, ie, neither notched nor deformed. This cup was masked by taper to hide internal reflections that otherwise produced confusing color changes.

Shallow grooving on five necks was noted as cosmetic blemishes (Fig. 3C, CB). In contrast, cup rims showed neither notching nor deformation (Fig. 5). EOS imaging

Fig. 6A–E This liner is positioned on the femoral head to show its rim contacting each of the three neck notches. (A) Oblique view of the superior notch (width 0.8 mm). (B) Oblique view of twin posterior notches (d1, p1). (C) Liner at the proximal posterior notch (p1) with polar impingement angle of 36° (head contained). (D) Liner at the distal posterior notch (d1) showing polar impingement angle of 14° (head subluxed). (E) Liner at the superior notch (d2) showing polar impingement angle of 14° resulting from head subluxation.

demonstrated cup impingement depending on patient posture in either standing or sitting. This varied with pelvic mobility and cup positioning. One femoral neck revealed unique superior notching (Fig. 6A). This patient had thigh pain while performing squatting exercises. Images taken in the squatting position showed cup impingement on the superior femoral neck and postural adjustment by pelvic rotation (Fig. 7). This particular femoral stem also had twin notches posteriorly. The proximal notch was a cosmetic blemish (Fig. 6B, p1) while the pronounced distal notch was 4 μ m deep (Fig. 6B, d1). With the liner positioned on

proximal (Fig. 6C) and distal notches (Fig. 6D–E), the corresponding polar impingement angles measured 36° and 14° , respectively.

Evidence of Normal and Adverse Wear Patterns

Normal wear patterns on femoral heads were slightly elliptical and covered areas of 490 to 900 mm² (Fig. 3C; Table 6). The centroidal vectors (CA) for these patterns averaged 16° in the superior direction. Four cups presented with contained main wear zone patterns (Fig. 3A); the

Fig. 7 This EOS image was taken with the patient in her novel squatting position to show the cup rim riding on the superior aspect of the femoral neck.

remainder showed rim breakout patterns (Fig. 3B; arcs averaged 216°). Cup wear areas ranged from 470 to 1050 mm². The resulting head and cup Hemi%-ratios averaged 56% with box plot data showing no statistically significant differences (Fig. 8).

Stripe damage was present in all cases (Fig. 9). All heads had basal stripes, two with eight and one with 10 (Table 7). Four femoral heads had polar stripes crossing within 5 mm of the pole and two cases showed multiple, crisscrossing polar stripes (Fig. 9). Polar and basal stripes frequently appeared collinear, even when separated by areas of polished surface. These aligned with the cup rims at impingement sites. Equatorial stripes were found adjacent to the inferior main wear zone boundary, sometimes appearing as one long stripe and sometimes as closely packed arrays of short stripes (Fig. 9A). These were located at nonimpingement sites. CoCr liners featured radial and circumferential stripe patterns with numerous basal stripes along some rims but were not investigated further.

Fig. 8 The main wear zone patterns (mm²) were compared for heads and cups using box plots.

Table 6. ‘Normal’ wear patterns (MWZ)

Patient number	Head MWZ arc (mm)	Angle CA	Head MWZ area (mm ²)	Head Hemi% ratio	Cup MWZ area (mm ²)	Cup Hemi% ratio	Ratio MWZ areas (cup/head)
1	39	35	900	0.73	509	0.41	0.57
2	31	7	653	0.53	567	0.46	0.87
3	29	6	591	0.48	646	0.52	1.09
4	37	14	887	0.72	754	0.61	0.85
5	29	28	536	0.44	467	0.38	0.87
6	32	19	699	0.57	774	0.63	1.11
7	35	9	789	0.64	914	0.74	1.16
8	27	22	489	0.40	485	0.39	0.99
9	34	9	786	0.64	861	0.70	1.10
10	29	11	557	0.45	1047	0.85	1.88
Average	32	16	689	0.56	702	0.57	1.05
SD	3.9	9.8	147	0.12	199	0.16	0.34

Arc = major arc of MWZ (mm); CA = angle between polar axis and the radial vector through MWZ centroid of the head; MWZ = main wear zone area (mm²) on heads and cups; Hemi% ratio = area of MWZ divided by hemispherical surface area of 28-mm metal on metal.

Fig. 9A–C The stripe wear patterns on the CoCr head were ink-marked to show relative positioning. **(A)** Polar, equatorial, and basal stripes. **(B)** Medial head view of two polar stripes showing stripe 1

tangent to the outer circle (diameter = 15 mm, site 1) and stripe 2 tangent to the inner circle (diameter = 6 mm; site 2). **(C)** Oblique view of head showing stripes 1 and 2 crossing each other.

Table 7. Stripe patterns on heads

Patient number	Polar	Equatorial	Basal
1	1	7	10
2	2	0	2
3	3	0	4
4	2	3	2
5	1	1	5
6	0	2	1
7	5	5	8
8	2	1	1
9	3	2	8
10	4	2	2

Impingement models demonstrated ROM varying from 124° with the Type A cup (narrowest neck) and reduced to 105° for a head with the skirt extension. Model 1 with the cup rim located at the proximal notch (see Fig. 6A) revealed polar impingement angle of 32° (Fig. 10A, head fully seated). Model 2 with the cup located on the more distal notch (see Fig. 6B) had polar impingement angle reduced to 12°, ie, head subluxation from the cup added 20° motion (Fig. 10B). The models showed that the head had subluxed 5 mm out of the cup, corresponding to the as-photographed position (Fig. 6). The damage tracks created by the cup rim (Fig. 9B–C; at impingement and subluxation) came within 7.5 mm and 3 mm of the polar axis, respectively (Fig. 10).

Evidence of Third-body Particles in the Joint

SEM imaging of stripes revealed wide scratches in both main wear and nonwear zones (Fig. 11). These varied considerably from less than 1 mm to tens of millimeters long, many ending in a smooth terminus. Scratch widths varied from 40 µm to hundreds of microns and frequently

exhibited edges raised 0.5 to 10 µm above the surface. Scratch valleys varied from submicron to over 20 µm deep. Contaminating layers of metal 0.5 to 10 µm thick were sometimes apparent, generally smearing onto the basal areas of CoCr heads. EDS imaging demonstrated metal elements containing titanium, aluminum, and vanadium (Ti, Al, V, respectively) and some iron (Fe) on one head.

Discussion

We found consistent evidence of impingement, abnormal MoM wear, and abrasion by large, third-body particles in this retrieval study of a single MoM THA. Prior reports cited revision of 28-mm THA subsequent to impingement and neck notching [19, 28, 49, 51, 57]. Our study appears to be the first implicating impingement with stripe wear on MoM bearing surfaces. The evidence was indicative of an in vivo damage mode whose existence, with the exception of one report on McKee-Farrar retrievals [27], was previously unsuspected.

Our study of 10 MoM retrievals was limited by the potential for patient-to-patient variability of the findings made. With only one male in this set of 10 retrievals, it could not be determined if there were sex-specific differences arising from variation in pelvic shape. This aspect is being investigated in an ongoing EOS-imaging project [40]. Our study is also specific to the femoral stem and cup designs used in these 28-mm MoM THAs. Our study set included two vendors, two cup types, and five stem geometries with differences in neck-length offset and neck diameters. The fact that this set of MoM all showed impingement (neck) and stripe (head) damage is not by itself proof that those findings led to revision. However, these data do illustrate that impingement in 28-mm THA may be a common pathway [3, 18, 22, 53, 64, 68, 80]. In support, a recent study noted impingement occurred in 83% of 28-mm and 32-mm CoC retrievals [20]. Such evidence

Fig. 10A–B The CoCr liner was positioned at impingement site 1 of twin posterior neck notches. (A) Liner on the proximal notch (see Fig. 6B: p1) formed a polar impingement angle of 32° with the head contained. This polar stripe was created within 7.5 mm of the polar

axis. (B) Liner on the distal notch (see Fig. 6B: d1) formed a polar impingement angle of 12° with the head subluxed. This polar stripe was created within 3 mm of the polar axis.

Fig. 11 The large, parallel scratches (1–4) in this SEM image following curvilinear tracks (arrows p–q–r) with typical dimensions 100 μm wide and several millimeters in length. This set of triple scratches changed direction 70° (from arrow P to arrow S). The focal surface depressions also indicated were the sites where metal debris impacted the surface (double arrow 5: feature = 100 μm width). Scale of the surface carbides (c: small circle and arrows) showed their associated surface scratches (s) were typically much smaller (scaling $\leq 1 \mu\text{m}$ width).

may indicate why some 28-mm MoM series showed good results over 7 to 15 years [13, 78] and others showed lesser success [4, 21, 41]. Because our 28-mm MoM retrievals were referred into La Pitie Hospital, the incidence of neck notching in the general population could not be determined.

Stem-notching evidence was unequivocal in our retrievals and could occur on both the anterior and posterior aspects of the femoral necks. The fact that circumferentially oriented neck notches coincided with the rim of CoCr liners confirmed that the damage was created in vivo and not during revision surgery. Modeling of 28-mm head, neck, and cup geometries showed that the proximal notch on the femoral neck represented the first impingement site

with the head fully contained, the cup showing a 32° polar impingement angle. Modeling the cup on the more distal notch demonstrated a 12° polar impingement angle at this point of subluxation. Thus, 20° of motion was produced by this head maneuver, which of itself would promote some “edge wear” of cup rims (Fig. 10). A similar levering phenomenon was evident in the EOS radiographs taken of one patient’s gymnastic ability. Squatting exercise produced superior notching in her femoral neck at a 14° polar impingement angle (compare Fig. 6B with 6C). This case illustrated that patient activities were also implicated in THA risk assessment. Evidence of twin neck notches was noted in our report of a 28-mm CoC bearing [19]. This earlier case had a history of squeaking and clicking noises. The decision was made to revise the THA when the surgeon noted a deep neck notch on her radiographs. At revision the femoral neck was found to have two deep notches and cup-to-neck impingement had also destroyed the posterior rim of the metal-backed cup (Ti6Al4V alloy). However, in our current study, the CoCr cup rims showed neither rim distortion nor notching. Therefore, femoral notching in our cases was a result of the cup rim habitually tracking across the same site on the neck, thereby producing wear over many repetitive impingement episodes [63, 64, 67].

Our patterns of “normal” or “habitual” cup wear do not indicate the degree of wear, only how much of the surface was used in vivo. When considering the concept of cup “safe” zones [48, 79], implant positioning was certainly suboptimal in our cases [41]. Thus, our assumption that such wear patterns were indeed “normal” may be incorrect. Simulator studies with large-diameter MoM have described wear areas mainly in cups [5, 44, 46]. In our 60-mm simulator study [5], the resulting Hemi% ratios represented 29% and 8% for heads and cups, respectively. In

this retrieval study, head and cup wear patterns were approximately equal with Hemi% ratios averaging 56% (Table 6). Thus, in vivo function used relatively more cup area than was present in simulator studies.

Stripe wear on femoral heads has been a common finding in CoC retrievals [16, 20, 54, 62, 70, 75, 76] but rarely mentioned in the MoM literature. It is possible that bearing damage could have been produced either by THA dislocation or alternatively by instruments used at revision surgery [8, 30, 60]. Ti6Al4V transfer onto CoCr surfaces could also be anticipated given the deep notching seen in titanium alloy necks in this study. We have found occasional evidence of metal transfer (elemental Fe, Ni) presumed to have originated from stainless steel instruments used at surgery. However, such transfer appeared as smears lying on bearings, whereas stripe wear abraded the CoCr surface. Also, recent computer modeling studies have indicated that the plastic deformation of MoM surfaces following “edge-loading” by cup rims appeared very similar to such stripe formations [55]. Therefore, we can confirm that stripe wear on 28-mm MoM retrievals was created in vivo. Nor were such abrasions random as previously suggested [27]. Our key observation was that stripe damage was preferentially oriented consistent with repetitive impingement. Thus, the patient’s hip motion arrested habitually at the same site, creating terminal basal and polar stripes as witness. Heads with multiple polar stripes indicated impingement had occurred in different positions. It is also realized that THA impingement and subluxation can occur as a result of soft tissue or bony interposition. However, neck notching was unequivocal in our 28-mm MoM group. The equatorial stripes were the least predictable and may have been created by the cup rim during normal gait, possibly as a result of (1) edge-loading (second-body wear) [27, 55]; (2) ingress of third-body abrasives under cup rims [26]; or (3) as a result of microseparation [32, 47].

Evidence for third-body wear by large particulates was also unequivocal in our study. CoCr surfaces showed the large scratches previously described in McKee-Farrar retrievals [27]. Their varied trajectories no doubt reflected the patient’s hip motion and loading permutations. The smooth terminus at the end of each scratch may indicate that the particles either rapidly decomposed or escaped from the articular surface and were again in circulation. It is to be noted that the half-life of such large CoCr particles is unknown. Case 1 was noted to have the highest form factor in the head and cup (Table 4), the out-of-roundness condition indicating high wear. The Ti6Al4V stem in this case featured a large notch created during multitudes of impingements (Fig. 3A). Thus, it may be surmised that clouds of metal particles and ions (CoCr, Ti6Al4V) were released into the joint space, contributing to third-body abrasive wear and

self-polishing [14]. We therefore find very good agreement with the earlier McKee-Farrar study [27].

In conclusion, the 28-mm MoM retrievals demonstrated consistent femoral impingement that could occur on either anterior or posterior facets of the neck. The stripe wear on heads represented concomitant damage resulting from combinations of second-body and third-body wear mechanisms. We can also speculate that with repetitive hip loading, the large circulating particles of CoCr produced during impingement [27] will quickly become pulverized into finer and finer debris. Thus, our model fits well with evidence of femoral neck notches, concomitant head stripe formation, 40- to 100- μ m abrasion tracks in CoCr bearings, self-polishing of CoCr surfaces, and the nanometer size debris recovered from tissues.

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