Isolation of polyacetal wear particles from periprosthetic tissue of isoelastic femoral stems

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We analysed revised Mathys isoelastic polyacetal femoral stems with stainless-steel heads and polyethylene acetabular cups from eight patients in order to differentiate various types of particle of wear debris. Loosening of isoelastic femoral stems is associated with the formation of polyacetal wear particles as well as those of polyethylene and metal. All three types of particle were isolated simultaneously by tissue digestion followed by sucrose gradient centrifugation. Polyacetal particles were either elongated, ranging from 10 to 150 μm in size, or shred-like and up to 100 μm in size. Polyethylene particles were elongated or granules, and were typically submicron or micron-sized.

Polyacetal and polyethylene polymer particles were differentiated by the presence of BaSO₄, which is added as a radiopaque agent to polyacetal but not to polyethylene. This was easily detectable by back-scattered SEM analysis and verified by energy dispersive x-ray analysis.

Two types of foreign-body giant cell (FBGC) were recognised in the histological specimens. Extremely large FBGCs with irregular polygonal particles showing an uneven, spotty birefringence in polarised light were ascribed to polyacetal debris. Smaller FBGCs with slender elongated particles shining uniformly brightly in polarisation were related to polyethylene. Mononucleated histiocytes containing both types of particle were also present.

Our findings offer a better understanding of the processes involved in the loosening of polyacetal stems and indicate why the idea of ‘isoelasticity’ proved to be unsuccessful in clinical practice.

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The development and introduction of the isoelastic femoral stem by Morscher and Mathys in the early 1970s aimed to solve two important problems in total hip replacement (THR): stress shielding and so-called ‘cement disease’. The isoelastic stem is manufactured from polyacetal (polyoxy-methylene copolymer POMC) resin which has a modulus of elasticity close to that of bone, i.e., approximately 5 and 13 GPa thus providing the condition of ‘isoelasticity’. The metal reinforcing steel core was introduced in order to achieve the required structural strength in the neck portion. Such a stem should allow loading of the bone to be more physiological. The collar transfers medial compressive forces to the calcar. Tensile forces are delivered to the lateral cortex by lag screws and rotational loading to the femoral cortex by lag screws and by the two wings.

The second object of isoelastic stems is to avoid the use of polymethylmethacrylate (PMMA) bone cement, which has been considered to be the ‘weak link’ in THR and the cause of osteolysis. In cementless isoelastic prostheses the proximal third of the stem has circumferential cross-hatching, and the lower two-thirds are quadrilaterally grooved to allow bone ingrowth and to provide long-term stability.

The short-term clinical results were optimistic. Andrew et al reported excellent results 28 months after operation: 92% of 400 patients had good function and only two needed revision surgery. The best results were achieved with the third generation of isoelastic prostheses, which showed a high degree of bone-prosthesis adaptability. Of 40 patients who had third-generation prostheses none required revision at six years after operation. Dick and Morscher reported that two-thirds of the isoelastic hips were rated good or very good 24 months after operation. Pišot noticed no significant differences between 169 patients with isoelastic and 95 with RCM-Ti cementless prostheses 61 months after operation, but long-term analy-
ses have shown that the late rate of failure was exceptionally high. Izquierdo and Northmore-Ball found that at 6.5 years after operation, the radiological rate of failure was over 50%. Matricali et al. analysed 19 patients at 4.8 years after operation. The results were very good or good in only half of the patients; one required revision. Träger stated that because there was a rate of loosening of the stem of 9.8%, the indication for implantation was restricted. Niinimäki, Puranen and Jalovaara proposed that regular radiographic checks are necessary for patients with isoelastic stems. A radiological rate of failure of 25% was reported and 12% of hips showed osteolytic foci. The longest follow-up study was reported by Trebse; 55 of 153 patients had had revision surgery by 12 to 15 years after operation.

The high rate of loosening of isoelastic stems may be related to biomechanical factors of interface stress and anomalous bone loading, and to biological factors such as chronic inflammation due to the formation of particulate debris. No attention appears to have been given to the possible formation and release of particles of polyacetal wear debris. The procedure for the isolation of polyethylene wear particles is now well established, but that for polyacetal particles has not been reported. Our aim therefore was to isolate and identify the polyacetal wear particles in periprosthetic tissues from failed isoelastic prostheses.

Patients and Methods

Between March 1998 and February 2000 we performed revision operations on eight patients with a mean age of 49.7 years (32 to 65) because of pain due to aseptic loosening of both the femoral and acetabular components. The patients had had THR for osteoarthritis at a mean of 9.99 years earlier (6.5 to 14.2). In all, the femoral component was a cementless isoelastic stem with a stainless-steel core (ISO 5832/1) and head (ISO 5832/1 (RM Mathys AG, Bettlach, Switzerland). The acetabular component was either an ultra-high-molecular-weight polyethylene (UHMWPE) cup of various sizes (RM Mathys AG) or a cemented cup (Cremascoli, Milan, Italy). Table I gives details of the patients and Table II of the original implants.

We subjected the removed implants to stereomicroscopy (ZH10, Olympus, Hamburg, Germany) and then SEM (JSM 5800; JEOL, Tokyo, Japan). The polyacetal cover was carefully cut from the stainless-steel core. UHMWPE cups were cut into sections. The samples were ultrasonically cleaned, attached to an SEM stub and sputter-coated with graphite. The compositional analysis of the surface was performed by energy dispersive x-ray analysis (EDA) (Link ISIS 300; Oxford Instruments, Oxford, UK).

### Table I. Details of the eight patients

<table>
<thead>
<tr>
<th>Case</th>
<th>Gender</th>
<th>Side</th>
<th>Age at revision (yr)</th>
<th>Implant in situ (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F</td>
<td>L</td>
<td>42</td>
<td>9.7</td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>R</td>
<td>45</td>
<td>14.0</td>
</tr>
<tr>
<td>3</td>
<td>F</td>
<td>R</td>
<td>57</td>
<td>8.7</td>
</tr>
<tr>
<td>4</td>
<td>F</td>
<td>L</td>
<td>58</td>
<td>9.9</td>
</tr>
<tr>
<td>5</td>
<td>M</td>
<td>L</td>
<td>32</td>
<td>14.2</td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>R</td>
<td>46</td>
<td>6.5</td>
</tr>
<tr>
<td>7</td>
<td>M</td>
<td>L</td>
<td>53</td>
<td>7.2</td>
</tr>
<tr>
<td>8</td>
<td>M</td>
<td>R</td>
<td>65</td>
<td>9.7</td>
</tr>
</tbody>
</table>

### Table II. Details of the removed prostheses

<table>
<thead>
<tr>
<th>Case</th>
<th>Stem*</th>
<th>Head*</th>
<th>Acetabular cup</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Length 150 mm (Klein L 150), width of the femur tip 8 mm</td>
<td>Ø 32 mm, height 34 mm</td>
<td>Ti-coated, No. 50, cementless, RM Mathys</td>
</tr>
<tr>
<td>2</td>
<td>Length 180 mm (Klein L 180), width of the femur tip 12 mm</td>
<td>Ø 32 mm, height 34 mm</td>
<td>No. 54, cementless, RM Mathys</td>
</tr>
<tr>
<td>3</td>
<td>Length 150 mm (Klein L 150), width of the femur tip 10 mm</td>
<td>Ø 32 mm, height 34 mm</td>
<td>No. 50, cementless, RM Mathys</td>
</tr>
<tr>
<td>4</td>
<td>Length 150 mm (Klein L 150), width of the femur tip 10 mm</td>
<td>Ø 32 mm, height 40 mm</td>
<td>No. 50, cementless, RM Mathys</td>
</tr>
<tr>
<td>5</td>
<td>Length 180 mm (Klein L 180), width of the femur tip 16 mm</td>
<td>Ø 32 mm, height 34 mm</td>
<td>No. 56, cementless, RM Mathys</td>
</tr>
<tr>
<td>6</td>
<td>Length 180 mm (Revisions S 180), width of the femur tip 16/14 mm</td>
<td>Ø 32 mm, height 34 mm</td>
<td>No. 54, cementless, RM Mathys</td>
</tr>
<tr>
<td>7</td>
<td>Length 240 mm (Reconstruction S 240), width of the femur tip 16/14 mm</td>
<td>Ø 32 mm, height 40 mm</td>
<td>No. 58, cemented, Cremascoli</td>
</tr>
<tr>
<td>8</td>
<td>Length 150 mm (Klein L 150) width of the femur tip 16 mm</td>
<td>Ø 32 mm, height 40 mm</td>
<td>No. 54, cementless, RM Mathys</td>
</tr>
</tbody>
</table>

* all RM Mathys
Germany) and placed on an orbital shaker overnight. They were rinsed with distilled water and then digested by 12 ml of 5M sodium hydroxide (Merck) at 65°C on a water bath-shaker. The digested solution was cooled to room temperature, ultrasonicated for ten minutes and then 7 ml placed into each of two clean centrifuge tubes and topped off with 5 ml of 50 wt % sucrose. We centrifuged the solutions for one hour at 6000 rpm (Centric 322A; Tehniča, Železnik, Slovenia). Polyethylene and polyacetal particles rose to the top of each tube. This band was carefully pipetted into another clean vial. Another band was formed on the bottom of the tube and was also collected. This contained polyacetal and in some cases also metal particles. To wash off the sucrose, we added 5 ml of distilled water, ultrasonicated for five minutes, and then heated for one hour at 80°C. The solutions were then topped off with 3 ml of isopropanol of density 0.785 g cm\(^{-3}\) (Carlo Erba, Milan, Italy) and centrifuged for one hour at 6000 rpm. The polyethylene and polyacetal particles formed a band, which was collected into a clean vial.

For SEM analysis, we filtered 10 to 200 \(\mu\)l of the particle solution through 0.2 \(\mu\)m of Nucleopore polycarbonate filter (Costar, Pleasanton, California). The filter was dried, attached to an SEM stub using double-sided tape, and sputter-coated with graphite. The composition of BaSO\(_4\) inclusions in polyacetal particles was verified by EDA.

The polyacetal and polyethylene particles were dried in air, tabletted with KBr, and then subjected to Fourier transform infrared (FTIR) spectroscopy (FTIR 1725X; Perkin-Elmer, Norwalk, Connecticut).

**Histological analysis.** Periprosthetic tissue samples for histological analysis were fixed in 10% formalin, embedded in paraffin, sectioned into serial sections 5 \(\mu\)m thick, stained with haematoxylin and eosin, and examined by a light and polarised microscope (BX50; Olympus, Tokyo, Japan) equipped with a digital camera (PVC 100C; Los Gatos, California). Selected samples were stained using Oil Red O\(^{14}\) to indicate the presence of polyethylene debris and polyacetal, and the sodium rhodozinate method as the standard histochemical method for barium staining.\(^{16}\)

Acute and chronic inflammatory cells, the number of mononuclear histiocytes and giant cells, the number and distribution of bone chips and the number and location of metal particles, as well as the area of necrosis and necrobiosis were analysed according to the modified Mirra classification.\(^{17}\)

**Results**

**Radiological findings.** Figure 1 shows typical radiographs after implantation and preceding revision surgery. The immediate postoperative film showed that the prosthesis was

![Fig. 1a (case 8)](image1)
![Fig. 1b (case 8)](image2)
![Fig. 1c (case 3)](image3)

Radiographs of the isoelastic prosthesis after implantation showing a) intimate contact between the implant and bone, b) massive osteolysis along the whole length of the prosthesis after 9.7 years in situ and c) migration of the prosthesis into the varus position after 8.7 years in situ.
firmly integrated into the bone (Fig. 1a, case 8). No radiolucent zones were observed, but nine years after operation the prosthesis had become loose (Fig. 1b). There was massive osteolysis with visible resorption zones along its whole length. Such extensive osteolysis often caused its subsidence and migration into the varus position (Fig. 1c, case 3).

Examination of prosthetic components. SEM of a new polyacetal femoral stem showed that on the microscopic level the surface was rough (Fig. 2a). Numerous elongated particles, loosely adherent to the surface, were observed. They were typically up to several tens of microns long. During the wear process in situ these elongated particles had obviously been removed since the surface of the replaced polyacetal stem was smoother and no elongated particles could be observed (Fig. 3a).

SEM using back-scattered electrons showed small, shiny inclusions identified as BaSO₄ (see Figure 4).

Figure 2a – SEM micrograph of the new polyacetal femoral stem recorded using secondary electrons showing that the original surface is rough, with elongated particles up to 100 µm in length. Figure 2b – Image recorded using back-scattered electrons shows small, shiny inclusions identified as BaSO₄ (see Figure 4).

Figure 3a – SEM micrograph of the worn polyacetal femoral stem recorded using secondary electrons showing that compared with Figure 2a the surface is smoother and there are no elongated particles. Figure 3b – Image recorded using back-scattered electrons shows small, shiny inclusions identified as BaSO₄ (see Figure 4).
After centrifugation with 50 wt % sucrose both polyethylene (density 0.94 g cm\(^{-3}\)) and polyacetal (density 1.42 g cm\(^{-3}\)) particles were present in the upper band. In addition, some polyacetal particles may also be found in the pellet but they are then contaminated with cell residue and thus are more difficult to analyse. The morphology of polyacetal particles was either elongated or shred-like. Large, elongated particles ranged from 10 up to 150 \(\mu\)m in length and were up to 5 \(\mu\)m wide (Fig. 5a). Shreds were irregular in shape and ranged up to 100 \(\mu\)m in length (Fig. 5b). Polyethylene particles were the predominant wear debris particles in failed isoelastic prostheses. Based on a rough estimate of the SEM images the proportion between polyethylene and polyacetal particles was at least one thousand-fold. Polyethylene particles were much smaller than polyacetal particles. There were two types: large, irregularly-shaped elongated particles of up to 20 \(\mu\)m in length, and smaller, elongated particles (fibrils) which were only a few microns in length (Fig. 6a). Granules were typically oval or spherical, with a smooth appearance and less than 1 \(\mu\)m in diameter.

FTIR spectra of both isolated polyethylene particles and reference polyethylene material (7 \(\mu\)m HDPE; Shamrock, Zevenaar, The Netherlands) showed typical peaks at 2917, 2850, 1470 and 721 cm\(^{-1}\). Theoretically, polyacetal could also be identified by FTIR showing typical peaks at 2920, 2860, 1490, 1450, 1390, 1250, 1100, 902, 630 in 450 cm\(^{-1}\). However, FTIR analysis of isolated polyacetal particles did not give sufficiently conclusive results. When we added artificially-made polyacetal particles to the tissue, digested it, and then isolated the particles, the FTIR spectra confirmed their presence. The identification of polyacetal particles in real tissue samples may be difficult because of their small quantity or a partial overlapping with some inorganic components.

We have therefore used the presence of BaSO\(_4\) inclusions, identified by back-scattered SEM as the only possible distinction between the two types of particle. This is clearly illustrated in Figures 5c, 5d and 6b. Whereas in the case of polyacetal particles BaSO\(_4\) inclusions were clearly seen as bright spots (Figs 5c and 5d), no such inclusions could be identified in the case of isolated polyethylene particles (Fig. 6b).

**Histological findings.** All the histological specimens showed severe fibrosis and typical granulation tissue consisting of macrophages and multinucleated FBGCs, as well as necrotic and necrobiotic areas. A distinctive finding was the presence of two types of FBGC. The first had large cells with particles of irregular, sometimes polygonal, shape (Fig. 7a). In polarised light these had an uneven brightness because of their spotty birefringence (Fig. 7b). Extremely large FBGCs of this type were up to 500 \(\mu\)m in length, but most were 100 \(\mu\)m. Numerous smaller, mononucleated histiocytes containing spotty particles were also seen (Fig. 7). This type of cell was described as a polyacetal-containing macrophage. The second type of FBGC contained typical slender, elongated polyethylene particles, which gleamed uniformly brightly in polarised light (Fig. 8). The polyethylene particles were up to 100 \(\mu\)m in size. In polarised light, numerous smaller polyethylene particles were seen in mononucleated histiocytes.

Positive Oil Red O staining for polyacetal and polyethylene wear particles was found in both types of FBGC and for cytoplasm in histiocytes. We used the sodium rhodazi-
nate method for the staining of BaSO₄ to distinguish between polyacetal and polyethylene particles.¹⁶ We expected positive staining for polyacetal particles in FBGCs, but unfortunately the method was unsuccessful. It seems that the process is unstable. When using the reference polyacetal bulk material the staining was successful but it disappeared with time.

Another important finding was the presence of bone chips of varying size primarily in necrobiotic areas and characterised by collagenous tissue without viable cells (Fig. 9). In two cases metal particles were seen as black dots in mononucleated histiocytes.

Discussion

The encouraging early clinical results³,⁴,⁷,⁸ with isoelastic polyacetal femoral stems have been overshadowed by long-term studies which revealed high rates of radiological failure and a high percentage of osteolytic foci.⁹-¹³ For these reasons this type of prosthesis is no longer in use. Our findings offer a deeper insight into the understanding of the process of loosening of isoelastic prostheses. We isolated three types of wear debris particle from periprosthetic tissue: a) polyethylene particles originating from the acetabular cup (Fig. 6); b) polyacetal particles from the femoral stem (Fig. 5); and c) metal particles from the metal head. The shred-like or elongated polyacetal particles were much larger than the submicron or micron-sized polyethylene particles and were up to 150 μm in length. The size and shape of the isolated polyacetal particles correspond to the surface features observed in unworn prostheses (Figs 2 and 6). Polyacetal and polyethylene particles were differentiated based on the presence of contrasting agent BaSO₄, which can be identified by back-scattered SEM analysis. Radiological analysis suggested a common pattern for loosened isoelastic prostheses (Fig. 1). Massive osteolysis and
Radiolucent zones were visible along the whole length of the prosthesis-bone interface. Conversely, radiolucent zones in cemented prostheses were always present at particular sites at the prosthesis-bone interface. Too much elasticity in the proximal part results in bone resorption and loosening and often forces the prosthesis into varus deformation. Histological examination showed two types of polymer wear debris. Extremely large FBGCs containing irregular, spotty gleaming particles were ascribed to polyacetal, whereas smaller FBGCs with elongated, uniformly brightly gleaming particles were related to polyethylene. The spotty appearance of the large wear particles may be related to the presence of BaSO₄ particles, which are pale white in polarised light because of their slight birefringency and strong refractility. Measurements of refractive indices were the basis for the differentiation of polyethylene and polyacetal wear debris by a simple optical method in histological samples.

Based on our results and on findings in the literature, we suggest that four factors affect the performance of isoelastic prostheses: stress shielding, micromovement, the formation of wear debris and the addition of contrast additives. Bypassing of the load to the proximal femur leads to so-called ‘stress shielding’ and eventually to bone resorption, disuse osteoporosis and failure of the implant. Polyacetal stems with a low elastic modulus should significantly decrease stress shielding and accompanying bone resorption. Recently, however, Niniimaki and Jalovaara have measured bone mineral densities 8.5 years after operation and observed a marked bone loss in the calcar region. The isoelastic prosthesis has a collar which should load the calcar and even the most proximal area of the femur and therefore preserve bone quality. This unexpected atrophy of the calcar region was explained by the stress bypass of the proximal femur, which then develops osteoporosis and even osteolysis.

**Figure 6**

Figure 6a – SEM micrograph recorded using secondary electrons of isolated polyethylene wear debris particles showing large elongated particles (E), fibrils (F) and granules (G). Figure 6b – Image recorded using back-scattered electrons shows a dark surface without shiny inclusions of BaSO₄.

**Figure 7**

Figure 7a – Photomicrograph showing an FBGC with a large irregular wear particle ascribed to polyacetal. Figure 7b – In polarised light this particle has an irregular, spotty birefringence.
The second factor related to the performance of the polyacetal stem is micromovement. Although polyacetal stems could significantly decrease stress shielding, they increase in proximal stem-bone interface stress, which may cause debonding and micromovement of the proximal stem at the interface. Burke et al have shown that cementless components are much less stable than cemented components in the stance where the highest hip contact forces and joint reaction forces occur. Consequently, the phenomena of micromovement may be more pronounced with isoelastic flexible stems than with stiffer metal stems.

The third factor affecting the performance of polyacetal stems is the production of wear debris. The formation of polyethylene debris originating from the acetabular cup is well understood and is comparable to that of other cemented or cementless systems. Hitherto, only three reports have assumed the possible formation of polyacetal wear debris. To our knowledge, our present findings offers the first proof of the isolation of polyacetal particles in periprosthetic tissues around failed isoeelastic stems. BaSO₄ and ZrO₂ are commonly added to bone cement as radiopaque additives and were introduced by Charnley. It was believed that these agents would not alter the mechanical properties of the cement and that they were biologically inactive. Recent studies have shown, however, that this is not completely true. These additives are harder than a metal femoral head and can damage the stainless-steel countersurface. Moreover, because of their particular size and composition they increase the biological reactivity of the cement debris in vivo.

Based on our results and findings in the literature we propose the following mechanism for failure of cementless isoelastic prostheses. The flexible stems may increase proximal stem-bone interface stress, thus causing debonding of the proximal stem and micromovement at the interface. It thus seems logical to assume that the first step in loosening would be mechanical. When the prosthesis-bone interface becomes imperfect and the undesired micromovement is untreated, the wear process starts and results in the formation of large amounts of polyacetal wear debris. During this process the inclusions of BaSO₄ may be pulled off from the polyacetal matrix. Since they are much harder than polyacetal or bone, they may then act as third-body wear particles. The shape and size of the isolated particles (Fig. 6), as well as the histological finding of the presence of large irregular wear debris and numerous bone chips (Figs 7 to 9) support the proposed mechanism for wear. The degree of the increase of polyacetal wear by BaSO₄ additives in the matrix is difficult to estimate, but their role in the wear process should be taken into consideration. An increased formation of polyacetal debris, combined with the normally occurring formation of polyethylene particles, leads to the accumulation of wear products at the interface and induces the formation of a pathological membrane including mononuclear and multinucleated histiocytes. This...
process disturbs the bone ingrowth and the stability of the implant resulting in loosening. Flexible isoelastic stems may allow polyethylene fragments from the socket to spread along the whole interface of the stem, more so if the proximal femoral bone does not maintain its density. This process additionally weakens the integrity of the anchorage. Finally, particulate wear debris can stimulate macrophages to produce mediators of osteolysis. Both the size and volume of polyethylene particles are critical factors in the activation of macrophages. Polyethylene particles in the phagocytosable size range of 0.3 to 10 μm appear to be the most biologically active. The biological activity of the much larger polyacetal particles which we also isolated is unknown and remains to be elucidated.

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