Influence of a foreign body on the wear of metallic femoral heads and polyethylene acetabular cups of total hip prostheses

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Excessive wear of polyethylene in total replacement hip prostheses elicits deleterious biologic reactions and may be thus a limiting factor that compromises the long-term performance of these devices. This study is based on the report of two clinical failures of total hip prostheses with metallic femoral heads and polyethylene acetabular cups. The investigations reveal that foreign bodies (titanium fibermesh pieces) can migrate into the joint space of total hip prostheses and participate in abrasive third-body wear of the polyethylene cups. This excessive wear of polyethylene enhanced by the modification of the metallic counterface roughness is likely to induce the early loosening of the devices.

1. Introduction

The implantation of hip joint prostheses is currently being performed worldwide at a rate of approximately 1000 per day [1]. Although the success rate has risen significantly and continuously, clinical failures are sometimes reported in the literature.

A hip joint prosthesis is a complex combination of components with various interfaces. The most functional of them is probably the acetabular cup/femoral head interface. For this interface, the majority of components implanted in patients consist of a highly polished metal or ceramic femoral head which articulates on an ultra-high molecular weight polyethylene (UHMWPE) cup. This acetabular cup may be fixed in place either with poly(methylmethacrylate) (PMMA) for elderly patients or with a metallic shell for younger ones. During walking activity, the joint components are subjected to wear in biological fluids. Consequently, clinical failures have been attributed to biological reactions due to wear debris and/or corrosion products generated at the articulating surfaces [2–8].

In fact, the success of total joint prostheses is related to numerous interdependent factors. In particular, a permanent fixation must be achieved as soon as possible [1]. In this way, surface treatments encouraging good anchorage through bony ingrowth are more and more performed for components in contact with bone. As an example, for younger patients, the polyethylene acetabular cup is usually fixed in a metallic shell coated with beads [9], fibermesh pieces [10] or hydroxyapatite [11]. Nevertheless, particular attention must be paid to the control of parameters during the coating process.

In the present study, two clinical cases of early loosening which involve a titanium fibermesh coating are reported. The aim was to analyse the consequences of the migration of titanium fibermesh pieces into the joint space on component damage (polyethylene acetabular cup and modular metallic femoral head). This study was based mainly on retrieved UHMWPE components articulated respectively on a titanium-based and on a cobalt-based femoral head. Both macroscopic and microscopic characterisations were performed and the results were compared with those obtained with similar non-implanted components or ones retrieved at the same follow-up but without titanium fibermesh pieces migration.

2. Experimental methods

Two UHMWPE hip joint cups retrieved because of extensive femoral osteolysis leading to early loosening have been studied. These cups retrieved respectively after 4.5 and 6 years where both inserted in a metallic shell Harris-Galante Mark I fixed with screws. The former articulated on a 28 mm titanium-based alloy femoral head (case A) and the latter on a 28 mm cobalt-based femoral head (case B). The chemical compositions of these alloys were in agreement with ASTM F136 and ASTM F75 respectively. For these two clinical cases, a titanium fibermesh piece inlayed in the polymer cup was detected by visual inspection (Fig. 1).

For each case, the macroscopic characterisation of damage consisted in locating the fibermesh piece with respect to the main direction of metallic femoral head penetration in the acetabular cup. After defining a frame of reference, the method consisted in measuring the deviations between points located on the internal surface of a cup and ones located on the theoretical surface of an hemisphere (diameter = 28 mm) using a coordinate measuring machine. The measurements were recorded in ten planes parallel to the top face of the cup flange at depth intervals of one mm. For each plane, measurements were performed at thirty six equally spaced angular positions around the cup. The deviations were therefore measured in three hundred and sixty directions for each acetabular cup.

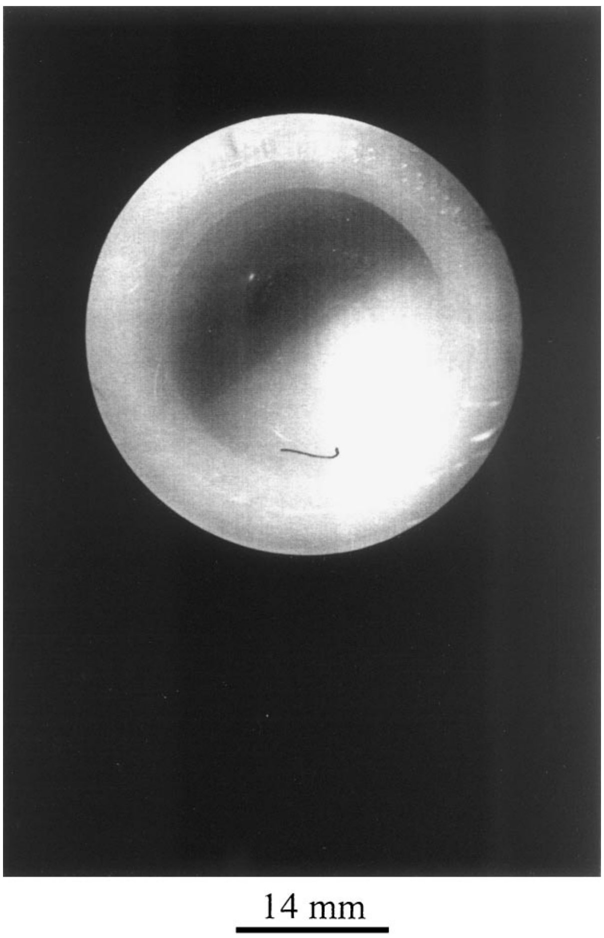


Figure 1 Photograph of a titanium fibermesh piece embedded in the polyethylene of the acetabular component.

The microscopic characterisation consisted in examining the surface damage of both femoral heads and acetabular cups using optical and scanning confocal laser microscopes. The last device has been used not only to observe the surface damage but also to quantify it recording surface profiles. A surface profile enables calculation of roughness parameters using a specific program on a personal computer. Average roughness has been used to quantify the damage of metallic femoral heads. For each observed area on a given femoral head, thirty profiles have been treated for the calculations. A complementary analysis was finally performed on the cobalt-based alloy femoral head using an EDAX (Energy Dispersive Analysis of XRays) system to identify the possible presence of titanium transfer due to fibermesh pieces into the joint space.

3. Results

Compared to a non-implanted polyethylene acetabular cup, the macroscopic analysis performed on the two retrieved acetabular cups shows that severe deformations occurred during lifetime. These deformations are presented on the stereographic projections in Fig. 2. These representations reveal clearly regions with excessive deformation for the two explanted acetabular cups. This localised damage is due to the penetration of the femoral head which involved both creep and wear. Some wear around the rim of the cups due to the impingement of the neck of the femoral stem is also evident.

The microscopic analysis carried out both on the external and on the internal surfaces of the retrieved acetabular cups reveals the disappearance of initial machining marks. The disappearance of such machining marks may be evidence of UHMWPE wear because of rubbing against the metallic shell for the external surface and against the femoral head for the internal surface. Consistent with several authors' results [12–14], two areas can be distinguished on the internal surface whatever the retrieved cup: a high-wear area and a low-wear area (Fig. 3).

The high-wear area has a smooth and highly polished surface compared to the low-wear area. The former area corresponds to the region of extensive macroscopic deformations in the effective direction of loading. In this area, an adhesive wear is likely to operate according to Atkinson *et al.* [12]. The fibermesh pieces detected are embedded in the low-wear area. In this area, some grooves having an identical shape to the fibermesh piece are detected by visual inspection. This last feature could be related to fibermesh pieces movement before their definitive location. Moreover, small scratches due to abrasive wear can be also observed.

Numerous small and multidirectional scratches are also visible on the metallic femoral heads of the explanted prostheses (Fig. 4). The scratch density is higher for the titanium-based alloy femoral head than for the cobalt-based one (Fig. 4a and b). This confirms the well-known fact that cobalt-base alloys offer a better

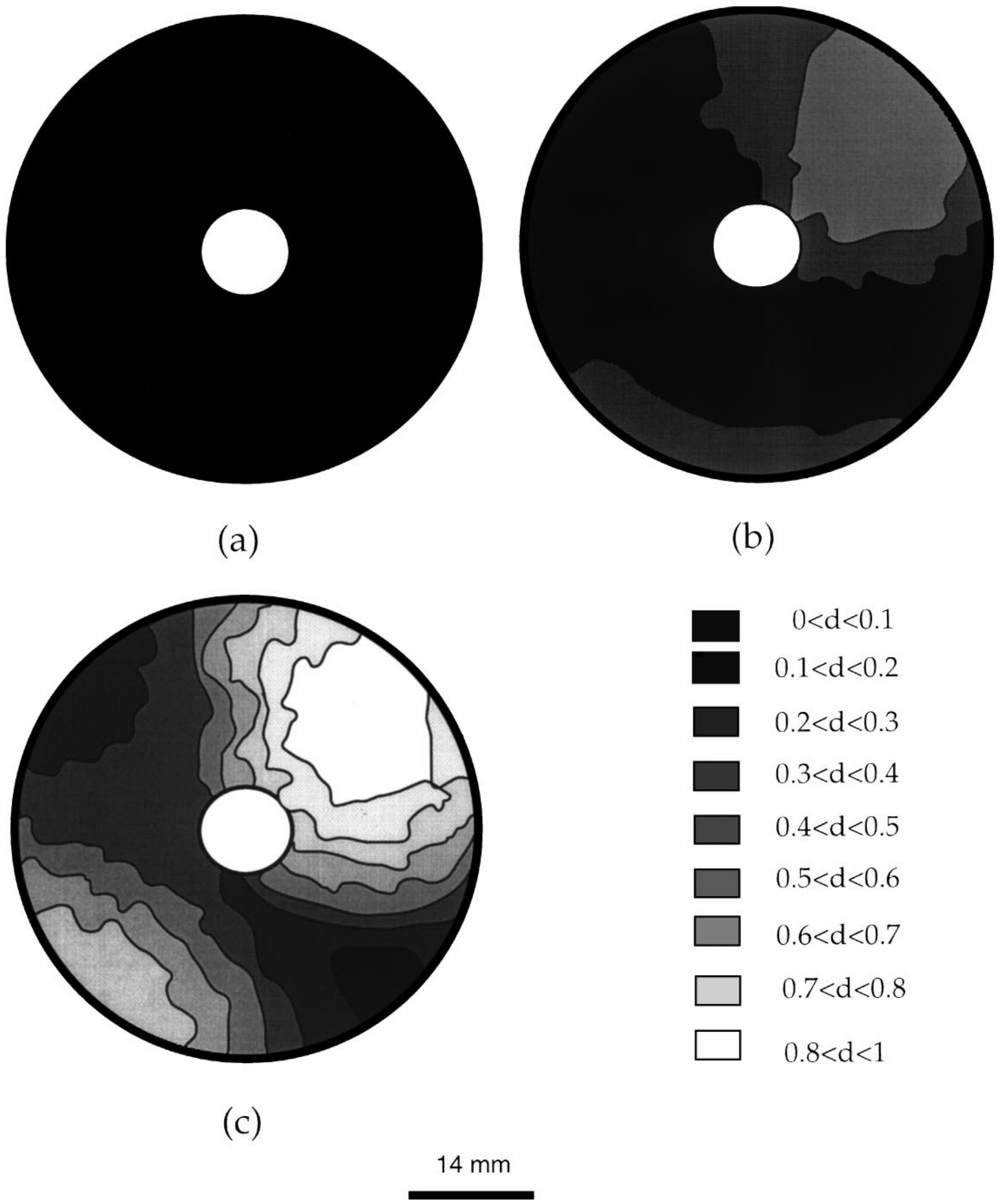


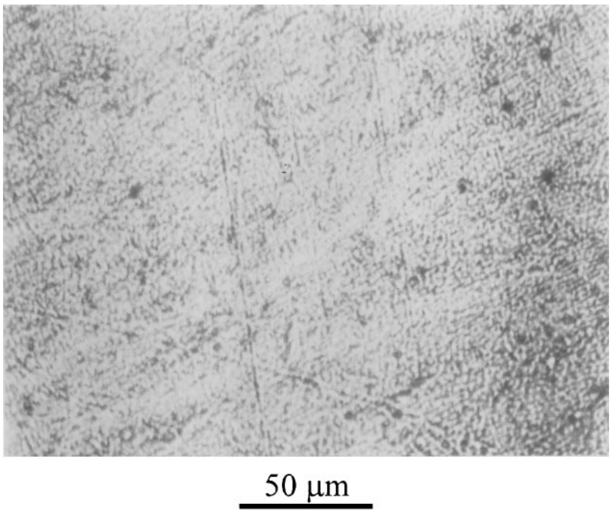
Figure 2 Stereographic projections of deviations (d in mm) between points located on a cup internal surface and ones located on a theoretical hemisphere surface (diameter = 28 mm) for: a) a non-implanted acetabular cup, b) case A acetabular cup, c) case B acetabular cup.

resistance to wear than titanium ones. For both femoral heads, two areas can be distinguished: a scratched area and a non-scratched area. For the titanium-based alloy femoral head, both fine and large scratches can be detected. Such large scratches have not been detected on a titanium-based femoral head retrieved at the same follow-up but without fibermesh pieces migration (Fig. 4a and c). These large scratches that can be seen in Fig. 4a are therefore likely due to abrasion with the embedded fibermesh piece.

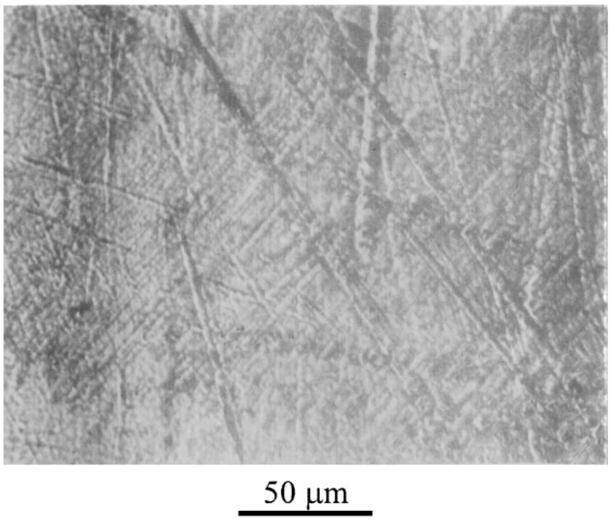
Typical surface roughness profiles recorded in the scratched and non-scratched areas of the titanium femoral head (case A) with the scanning confocal microscope are presented in Fig. 5. Surface roughness measurements of all femoral heads are presented in Table I. Whatever the alloy, the average roughness values indicate that the damage is greater for femoral heads in contact with fibermesh pieces than that observed for the same femoral heads retrieved at the same follow-up or for the highly polished finish of new prostheses.

For the cobalt-based femoral head, black marks have been detected in the scratched area (Fig. 6). An EDAX analysis of the local chemical composition associated with these marks compared to that of the bulk reveals a relatively high level of titanium (Fig. 6 and Table II). Because titanium is not present in the initial composition of the cobalt-based alloy, the presence of this element peak is therefore likely due to debris from the loose fibermesh piece.

The previous reported results suggest that the embedded fibermesh pieces are involved in a third-body wear mechanism.



(a)



(b)

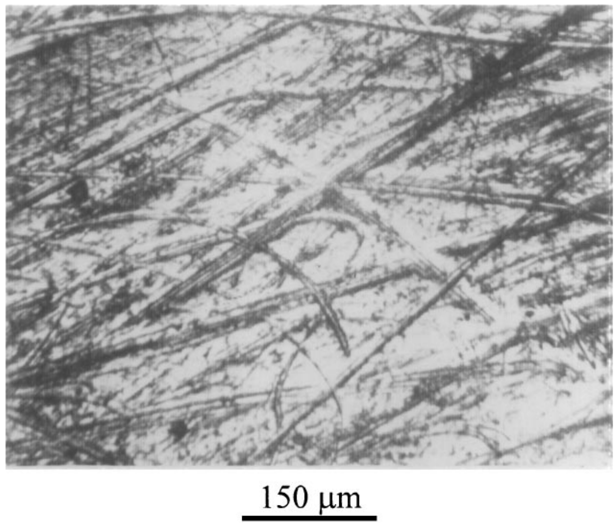
Figure 3 Photographs showing general features of: a) the high wear area, b) the low-wear area.

4. Discussion

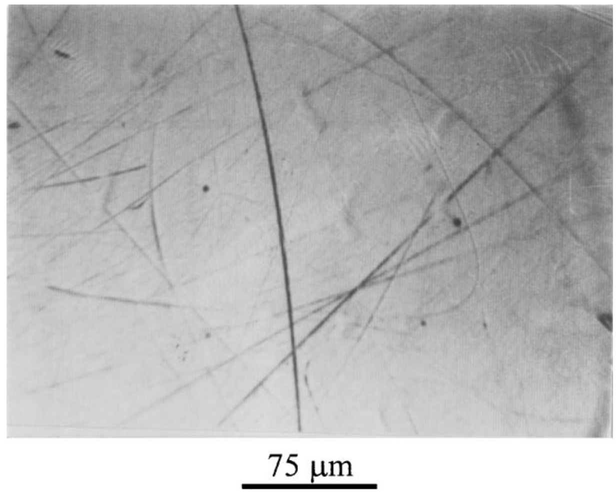
An engineering approach of total joint replacement is very complex and highly interdisciplinary, involving materials, mechanical, environmental and biological parameters [2].

A primary objective of total joint replacement is to achieve permanent fixation as soon as possible increasing interfacial strength between implant and bone [1]. An increased interfacial strength results in a better stress transfer to the surrounding bone and a more uniform stress distribution around and in the implant. Theoretically, a stronger interfacial bond will decrease the propensity for implant loosening [2]. Thus, surface treatments enhancing bone ingrowth have been developed to improve the interfacial bond between implant and bone. Nevertheless, the process parameters must be carefully controlled to prevent adverse effects which can lead to an early loosening.

In the present study, two clinical cases of early loosening involving fibermesh coating have been reported. The components were retrieved after 4.5 and 6 years respectively whereas the accepted, and expected, goal for primary total joint replacement is that patients can continue their activities remaining relatively pain free without revision up to twenty years after implantation.



(a)



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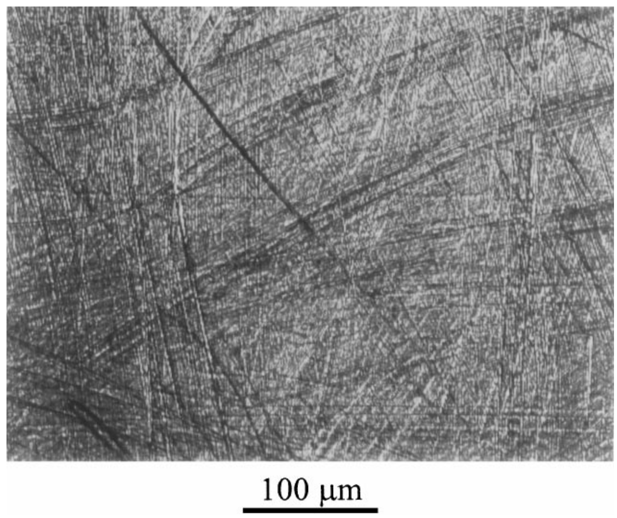


(c)

Figure 4 Photograph of the numerous multidirectional scratches on the surface of the: a) titanium-based alloy femoral head in contact with fibermesh piece. The large scratches are likely due to abrasion with the embedded fibermesh piece. b) cobalt-based femoral head in contact with fibermesh piece, c) titanium-based femoral head retrieved at the same follow-up but without fibermesh pieces migration.

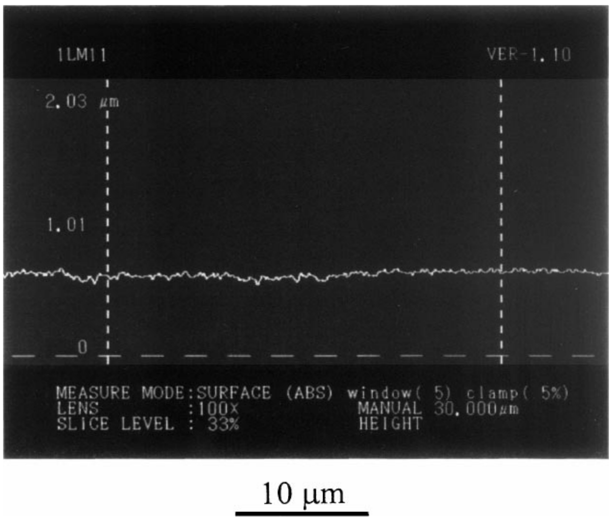
Both macroscopic and microscopic characterisations show that a fibermesh piece of a metallic shell coating can migrate into the joint space, become trapped between the articulating surfaces of the femoral and acetabular components and participate in abrasive third-body

TABLE I Surface roughness measurements. R_a is the average roughness and σ the mean standard deviation. Each value represents the mean of thirty measurements

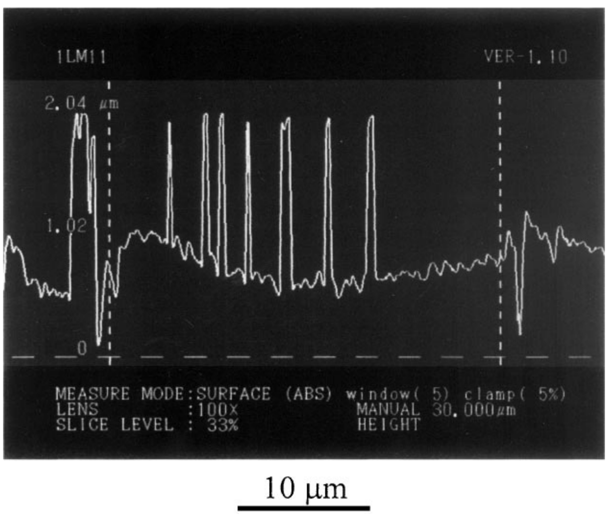
Alloy	Area	R_a (μm)	σ (μm)
Ti6A14V(A)	non-scratched	0.07	0.02
	scratched	0.26	0.03
CoCr (B)	non-scratched	0.06	<0.01
	scratched	0.07	<0.01
Ti6A14V/Same follow-up as (A)	non-scratched	0.07	0.01
	scratched	0.13	0.01
CoCr/Same follow-up as (B)	non-scratched	0.05	<0.01
CoCr Non-implanted	non scratched	0.04	<0.01

TABLE II Comparison between local chemical composition (only main elements) of the black marks detected in the scratched area with that of the bulk for the cobalt-based alloy femoral head (case B)

CoCr (Case B)	Co	Cr	Mo	Ti
Bulk	Balance	28.2	6.6	0
Black marks	Balance	28.2	5.4	4.5

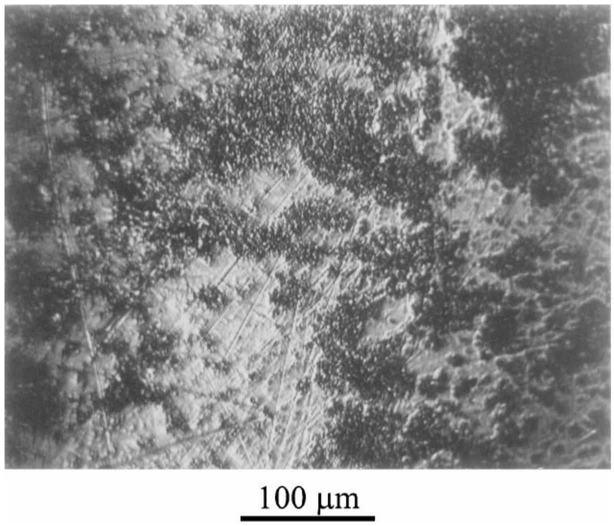


(a)

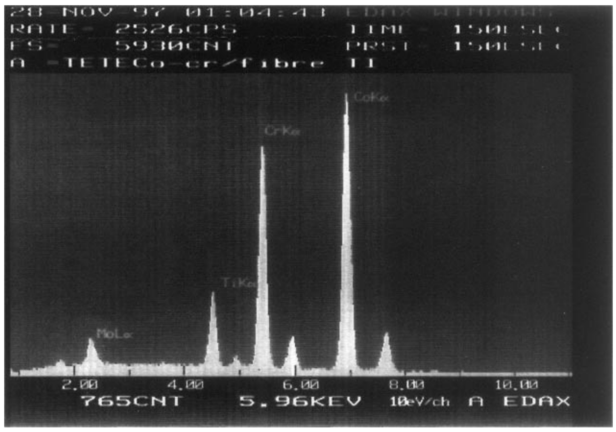


(b)

Figure 5 Typical surface roughness profiles recorded at a magnification 2000 on the titanium based-femoral head in contact with fibermesh piece: a) non-scratched area b) scratched area.



(a)



(b)

Figure 6 Photograph (a) and EDAX spectrum (b) of the black marks detected on the cobalt-based alloy femoral head. These black marks are likely due to abrasion with the embedded fibermesh piece.

wear. Both the polyethylene acetabular cups, the metallic femoral heads (whatever the nature of the alloy) and the surface of embedded fibermesh pieces had numerous multidirectional scratches consistent with third-body abrasive wear. The fibermesh pieces presence into the joint space is likely to enhance polyethylene wear through the modification of the metallic femoral head roughness. Indeed, some authors have shown that a single defect in the counterface can cause a dramatic increase in the wear rate of UHMPWE [15] and the roughness of the counterface is thus an important contributory factor to wear [4, 6, 16, 17].

Our results are consistent with those reported by numerous authors. These authors found that the production rate of polyethylene debris can be accelerated by the interposition of hard particles in the joint space. These can be particles of bone cement [12, 17, 18], metal beads from porous coating [9, 19], broken wires [20–22], and particles of bone. Small metal particles from modular interfaces or from surgical instruments have also been implicated [23].

While UHMWPE is well tolerated within the body in bulk form, it is now recognised that the biological response to wear debris is one of the main mechanisms of aseptic loosening of metal-polyethylene total hip replacements [4, 8, 24]. Study of pseudomembranes from such cases has shown that polyethylene particles generated by friction at both articular and non-articular interfaces are the most frequent component of these debris. They are found in considerable concentrations in the periprosthetic tissues and are associated with intense cellular reactions. These are characterised by the presence of stimulated macrophages which secrete mediators of bone resorption. Accelerating the rate of polyethylene debris formation by interposing a hard particle in the joint space will therefore be likely to induce an early failure of the total hip replacement.

5. Conclusions

In this study, it is shown that titanium fibermesh pieces of a metallic shell coating can migrate into the joint space, become trapped between the articulating surfaces of the femoral and acetabular components and participate in abrasive third-body wear of polyethylene.

The polyethylene wear is associated with the evolution of metallic femoral heads roughness. So, metallic debris may be also involved in early loosening of total joint prostheses.

Fibermesh fixation to the metallic shell should be improved and the coating process should be carefully controlled to avoid deleterious effects.

Acknowledgements

This study was financially supported by the Fédération des Biomatériaux Nord-Pas de Calais. The authors would like to thank Mr. T. Coorevits and Mr. J. C. Vervisch for their technical assistance and scientific discussions.

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Received 30 July 1999
and accepted 10 February 2000