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Detailed three-dimensional size and shape characterisation of UHMWPE wear debris

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ABSTRACT

Atomic force microscopy (AFM) is used to characterise UHMWPE wear debris from a knee prosthesis actuated under constant load. The size and shape of debris particles is quantified in all three spatial dimensions. Artificially limiting the analysis to the two-dimensional projections of the particles onto the substrate plane, it has been found that equivalent shape ratio (ESR) plotted as a function of equivalent circle diameter (ECD) follows a trend observed before. Inclusion of the third, vertical spatial dimension of particle height shows that such two-dimensional analysis, as it is often based on SEM images, can greatly misrepresent the actual particle shape. The three-dimensional AFM information indicates that for the prosthesis and the conditions studied here debris particles tend to be deformed independent of their volumetric size. Fractionation of debris particles according to size was achieved with a new filtration protocol. It is demonstrated that with this protocol debris particles settle uniformly across the filter and that particle abundance as function of size can thus reliable be established.

1. Introduction

Ultra high molecular weight polyethylene (UHMWPE) is the selected material for tibial inserts and patellar components in total knee arthroplasty due to its low wear rate, excellent abrasion resistance and high mechanical stability [1,2]. In spite of the adequate material properties, wear is observed because of the highly dynamic stresses experienced in a knee joint.

The polyethylene wear debris generated with these mechanisms affects the clinical performance of the joint. Particle debris stimulates the generation of a membrane at the interfaces between prosthesis and bone. This membrane is highly populated with macrophages. Phagocytosis, i.e. the interaction between macrophages and debris particles, provokes the release of cytokines and other mediators of inflammation. Furthermore, osteoclasts are activated, which then resorb bone, leading to prosthesis loosening. As polyethylene particles are not digestible by macrophages, the debris is eventually ejected from the macrophage only to be phagocytized again [3,4].

The abundance of UHMWPE debris particles influences their bio-response. Ingram et al. [5] e.g. concluded that a volume of 50 μm^3 of UHMWPE particles per macrophage cell induces the release of cytokines with the debris particles being in the size range of 0.1–1 μm. This particle size range is generally considered particularly bioactive. However, published work differs in regards to the limits of that range. For example, some references quote a range of 0.1–10 μm [6,7], whereas Green et al. suggest 0.3–10 μm [8] and Mathews et al. limit the range of most biologically active particles to 0.24–0.45 μm [9]. Those authors measured the same cytokine signals and used similar experimental conditions with typically 24 h of cell culture incubation and particle-to-cell ratios of 100:1 and 10:1. The shape of the particles plays a role since irregularly shaped particles show an increased biological reactivity [10,11,14]. Abundance, size and shape of UHMWPE wear particles are thus critical parameters for bioactivity studies. It is important that these parameters are correctly determined.

Fractionation of different debris particle sizes has often been achieved by filtration and images of the debris on the filter are typically obtained by scanning electron microscopy (SEM) [10,11,15–18]. SEM determines the two dimensional projection of a particle onto the substrate and gives some qualitative contrast information about the particle height. This may be problematic because the actual three dimensional shapes of particles have to be inferred from the two dimensional projections.

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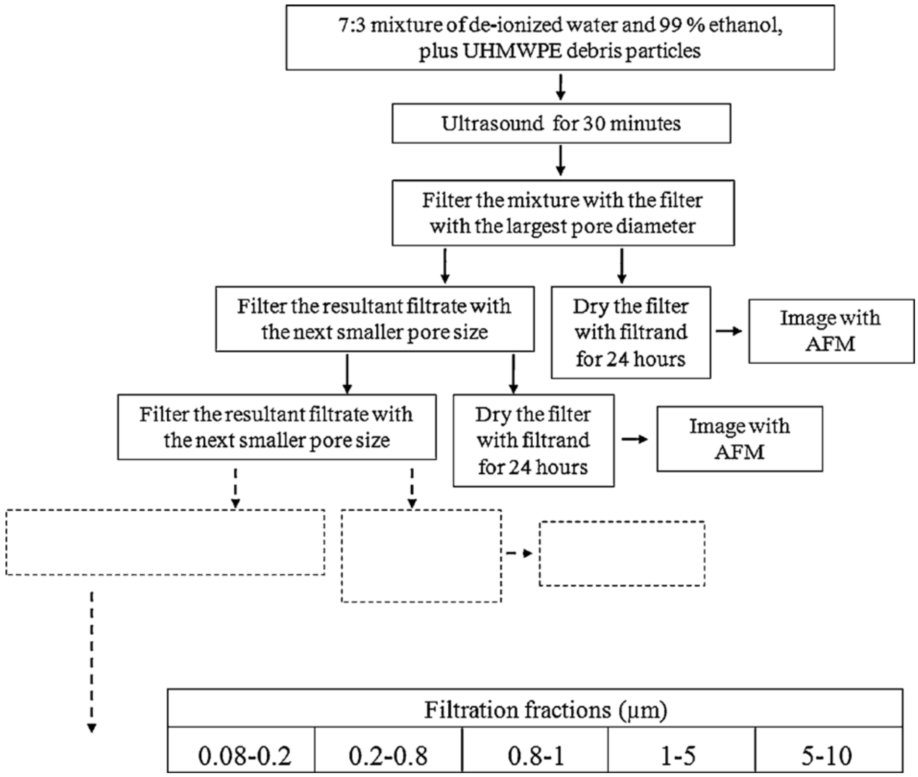

Fig. 1. Flow chart illustrating the new filtration protocol applied in this work. The limits of the filtration fractions obtained are given in the figure.

With atomic force microscopy (AFM), in contrast, the size and geometry of polyethylene wear particles can be measured in all three spatial dimensions with a precision on the nano-metre scale [19]. This has the potential of improving the quality of information available about the size and shape of debris particles. Correct morphological data on debris is also relevant to determining the frequency of particles as a function of volumetric size in fractionated abundance distributions. AFM imaging has rarely been applied to characterise UHMWPE debris [19–21]. However, Scott et al. [20] have demonstrated consistency with SEM.

In the determination of fractionated abundance distributions it is often assumed that particles precipitate uniformly over the filter medium during filtration. Some authors [10,11] have verified the uniformity of particle distributions by imaging several locations of the filter. Our previous work [19] concluded that a quantitative verification of uniform debris settling across a filter is essential in order to establish reliable abundance distributions of wear particles.

In the present study a new experimental protocol has been developed to obtain uniform precipitation of particles over a filter medium. Atomic force microscopy has been applied to verify the uniformity of precipitation. The size and shape of particles has been measured directly in three spatial dimensions.

2. Materials and methods

A pristine knee prosthesis was actuated with a constant load knee actuator [19] in order to obtain UHMWPE wear debris particles. The prosthesis was a standard size, cobalt-chrome on UHMWPE, low contact stress (LCS) mobile bearing knee system (DePuy/Johnson & Johnson). The actuator simulates the flexion-extension motion of the knee joint [22,23]. During the simulation the axial force is kept constant. Since the focus of this work is on the spectrum of debris particles and their characterisation, water was used rather than bovine serum. Aliquots of the water lubricant containing wear debris were collected regularly and samples were prepared for AFM characterisation.

2.1. Constant load knee actuator

In an attempt to coarsely approximate a ‘walking’ actuation of the prosthesis, a stance and a swing phase were simulated dynamically. Every testing interval was divided into two distinct parts (see [19] for details). The first part (35% of one testing interval) with

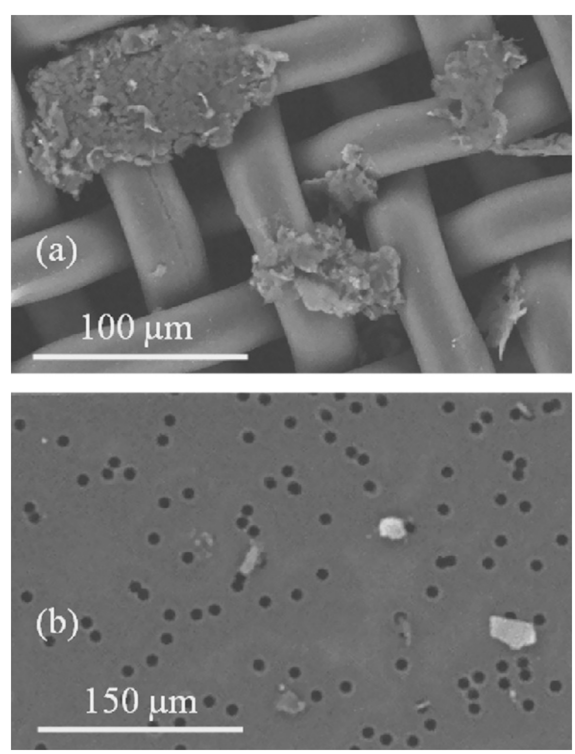

Fig. 2. SEM images of wear particles on (a) a 10 μm and (b) a 5 μm filter.