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Release of zirconia nanoparticles at the metal stem–bone cement interface in implant loosening of total hip replacements

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A B S T R A C T

In a previous failure analysis performed on femoral components of cemented total hip replacements, we determined high volumes of abraded bone cement. Here, we describe the topography of the polished surface of polymethyl methacrylate (PMMA) bone cement containing zirconia radiopacifier, analyzed by scanning electron microscopy and vertical scanning interferometry. Zirconia spikes protruded about 300 nm from the PMMA matrix, with pits of former crystal deposition measuring about 400 nm in depth. We deduced that the characteristically mulberry-shaped agglomerates of zirconia crystals are ground and truncated into flat surfaces and finally torn out of the PMMA matrix. Additionally, evaluation of in vitro PMMA-on-PMMA articulation confirmed that crystal agglomerations of zirconia were exposed to grain pullout, fatigue, and abrasion. In great quantities, micron-sized PMMA wear and zirconia nanoparticles accumulate in the cement–bone interface and capsular tissues, thereby contributing to osteolysis. Dissemination of nanoparticles to distant lymph nodes and organs of storage has been reported. As sufficient information is lacking, foreign body reactions to accumulated nanosized zirconia in places of long-term storage should be investigated.

Statement of Significance

The production of wear particles of PMMA bone cement in the interface to joint replacement devices, presents a local challenge. The presence of zirconia particles results in frustrated digestion attempts by macrophages, liberation of inflammatory mediators, and necrosis leading to aseptic inflammation and osteolyses. Attempts to minimize wear of articulating joints reduced the attention to the deterioration of cement cuffs. We therefore investigated polished surfaces of retrieved cuffs to demonstrate their morphology and to measure surface roughness. Industrially admixed agglomerates of the radiopacifier are abraded to micron and nano-meter sized particles. The dissemination of zirconia particles in the reticulo-endothelial system to storage organs is a possible burden. Research to replace the actual contrast media by non-particulate material deserves more attention.

1. Introduction

1.1. Background

Resorption of anchoring bone due to a foreign body reaction at the device-bone interface is a major complication in aseptic loosening of cemented total joint replacements [1,2]. The loss of constraint [3] resulting from an intermediate layer of soft tissue and mechanical overload have been ascribed to fragmentation of the cement mantle (polymethyl methacrylate, PMMA). Among others, Wang and co-workers based their criticism of the clinical performance of cement anchorage on the production of cement debris. They concluded that significant synergistically pathological reactions to the polymer containing customary radiopacifier (barium sulfate or zirconium dioxide (zirconia)) not only impair articulation of the joint, but also contribute to bone resorption [4]. In the granulation tissues of the cement–bone interface, macrophages with foamy cytoplasm have been described as containing micron and submicron wear particles. Additionally, giant cells engulf

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greater particles representing PMMA pearls and matrices, fragments thereof, and conglomerates of zirconia contrast media [5]. During mechanical loosening, instability and relative motion of anchoring stems under loading create abrasion of both metal component and contact surfaces of bone cement within a relatively short time. The loss of submicron material from cement mantles may reach volumes as high as of up to 1 or 2 cm^3 [6].

In previous studies, we observed cases of implant loosening over several years with displacement and rotation of the stem resulting in moderate but persistent abrasion of bone cement particles [7]. Light microscopic examinations of interface granulation tissues have demonstrated predominant storage of zirconia contrast medium that were measurable within the detection limit range of light microscopy (diameter of about 0.5 μm). No fragments of PMMA pearls and matrix were present. The well-described mulberry- or cauliflower-shaped agglomerates of the admixed zirconia radiopacifier or its larger fragments were not found in these granulation tissues by our studies. Repetition of foreign body reactions to nanoparticles of the zirconia radiopacifier after apoptosis of resting macrophages may initiate and sustain mediator-induced activation of osteolysis (frustrated digestion) [8].

Widespread dissemination of particulate foreign material and accumulation in distant organs has been well described [9,10]. Foreign body reactions to micron- and nanoscaled zirconia particles in particle accumulation sites represent possible health hazards that deserve closer follow-up of total joint replacements with long-term function and post mortem histopathology whenever possible.

1.2. Aims

Limited information is available on the morphology of worn PMMA surfaces, the fate and behavior of the zirconia conglomerates, and on the generation of wear products. Herein, we continue a retrieval analysis of cemented total hip replacements. In the previous publication [6], failure induction and propagation was attributed to special implant design features, positioning in the cement dough, and sandblasted surfaces of the implanted femoral device. The metal stem rubbed against the PMMA bone cement and abraded the polymer matrix as well as the zirconia conglomerates added as radiopacifier. Our analysis demonstrated cement surfaces polished to a high finish quality [6].

Here we analyzed the topography of polished zones, and sizes of structures within zirconia agglomerates and of crystals were measured. We observed in vitro preparations of the basic material for comparison of surface characteristics with retrieved samples. As no information on the bonding strength of the zirconia within the PMMA and the coherence of agglomerated crystals was available, we surmised that a moderate in vitro process of abrasion would demonstrate whether disintegration and polishing of zirconia agglomerates is probable. Our aim was to test the hypothesis that movements of the femoral shaft relative to the cement cuff liberate nanoparticles and additionally deteriorate agglomerates of the radiopacifier zirconia.

2. Materials and methods

2.1. Origin of materials

Over a 9-year period, 393 total hip joint replacements ("CF-30" femoral stems, stainless steel – ISO 5832-9 and all-polyethylene sockets made of UHMW-PE – ISO 5834/1 type A and manufactured by Sulzer Orthopedics AG, Winterthur, Switzerland) were implanted in patients. Throughout all procedures, Palacos R® bone cement (plain PMMA cement with ZrO_2 radiopacifier, Heraeus AG, Wehrheim, Germany) was prepared by vacuum mixing and inserted by antegrade syringe application. Alumina ceramic balls (Biolox ®, CeramTec AG, Plochingen, Germany) completed the joint replacement (Fig. 1a). A high, above-average number of femoral components (about 9.5% after an implantation period of 5 years) had to be removed due to aseptic loosening following mechanical failure of the cement mantles and overload of bone. During replacement surgery, intermediate layers of soft tissue facilitated extraction of cement mantles. The surgeons attempted to extract segments as large and unimpaired as possible (Fig. 1a). In a previous retrieval analysis [6] of 37 retrieved total joint replacements (stems and cement mantles), the fragments were cleaned in detergent, sonicated and rinsed with tap water, and finally dried and stored in the dark at room temperature. The original position of the fragments was mapped.

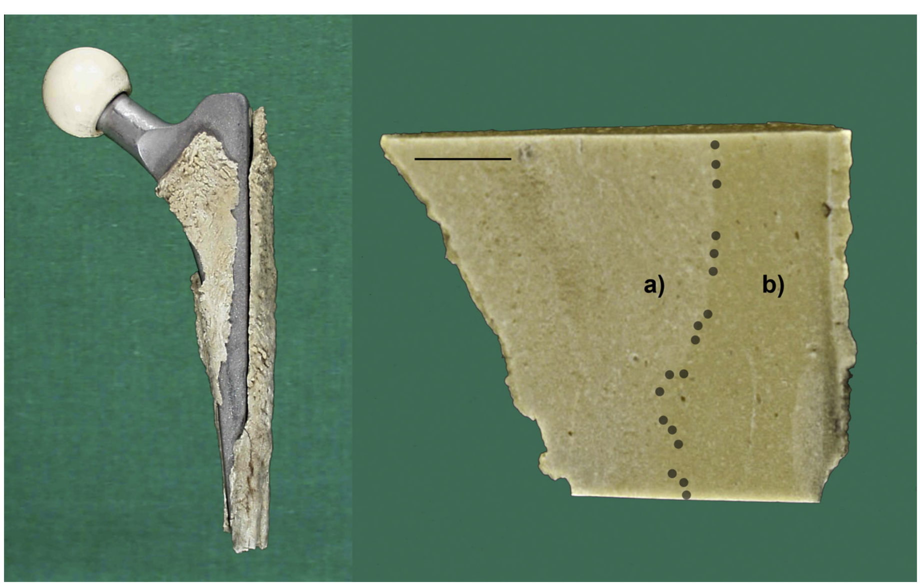

Fig. 1. (a) Retrieved CF-30 femoral stem with rearranged fragments of cement mantle. Note fragmentation, inappropriate thinning of cement mantle and cementing defect leading to metal-bone contact. Ball head diameter 28 mm. (b) PMMA macro: part of cement mantle fragment from the ventro-lateral side at the lower proximal third of the mantle, lower (distal) and upper (proximal) cuts are rectangular to the axis of the stem. The left border corresponded with the medial bow of the stem, the right with the lateral side. Two zones, (a) of original primary contact and (b) deteriorated by abrasion and polishing, depict the surface of metal contact. The bar measures 5 mm.