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Wear analysis of cross-linked polyethylene inserts articulating with alumina and ion-treated cobalt-chromium femoral heads under third-body conditions

Jessica Hembus*, Laura Lux, Mario Jackszis, Rainer Bader, Carmen Zietz

Biomechanics and Implant Technology Research Laboratory, Department of Orthopaedics, University Medicine Rostock, Doberaner Str. 142, 18057 Rostock, Germany

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ABSTRACT

Aseptic implant loosening due to wear debris is the main cause of revision of total hip replacement. Since the presence of third-body particles in the joint gap can lead to highly increased amount of wear, the aim of this study was to evaluate wear of hard-on-soft couplings under third-body wear conditions.

For this, alumina ceramic and nitrogen ion-treated cobalt-chromium femoral heads were coupled with sequentially cross-linked polyethylene inserts in a hip joint simulator following ISO 14242-1. Bone cement particles containing zirconium dioxide were added. After 5 million cycles, the amount of wear on the inserts was determined gravimetrically and compared to the amount of wear without third-body particles. The abrasion at the joint components was evaluated by digital microscope.

The mean gravimetric wear rates of the polyethylene inserts under third-body wear conditions measured 16.57 ± 5.98 mg per million cycles when coupled with nitrogen ion-treated CoCr heads and 15.14 ± 3.30 mg per million cycles with alumina ceramic heads. The results revealed no significant differences between the material pairings. The amount of wear was approximately eight times higher in both cases than that resulting under standard wear test conditions. In the microscopic analysis, the ceramic femoral heads showed higher resistance against abrasive third-body wear.

1. Introduction

The main cause of total hip revision is aseptic implant loosening due to particle-induced osteolysis, which is initiated by abrasive wear particles [1,2]. Third-body wear in particular increases the amount of wear of the polyethylene components and accelerates the effect of osteolysis [3]. Moreover, the third-body particles directly transfer increased frictional forces to the artificial implant junction, which leads to a higher loading at the implant-bone interface [4]. One possible method of reducing wear debris is to use low-wear bearings like hard-on-soft bearings, as successfully proven in experimental studies in recent years [5,6]. These studies revealed better frictional properties and less wear when using ceramic-on-polyethylene bearings compared to metal-on-polyethylene bearings [7,8]. Moreover, by using biologically inert and scratch-resistant materials like ceramic implants, the incidence of allergic reactions to metallic, abrasive wear particles can also be reduced [7–11].

By increasing the surface hardness of cobalt-chromium femoral heads, the amount of wear debris can be reduced [12]. In a wear simulator study by Fabry et al. [13], similar amounts of wear were reached when analysing ion-treated CoCr vs. Al2O3 ceramic heads, both articulating with polyethylene inserts.

Due to third-body particles in the joint gap, there is likelihood of abrasion of the joint being highly intensified [9,14,15]. The third-body particles can originate from different materials, mainly from bone and bone cement, but also from metallic or ceramic components, and be induced by different causes [16–18]. For instance, these particles can be generated during implantation of the total hip endoprosthesis, by implant fractures or by relative motion between the bone-implant interface [17–19]. The size of the bone cement particles found during total hip revision and removing is rarely examined, and varies from a few microns to over 1 mm [20]. Lundberg et al. [21] found third-body particles of approximately 50–500 µm or more embedded in explanted acetabular polyethylene inserts.

There are many standard hip simulator tests, but only a few under third-body conditions [8,13,22]. Mostly, the studies are not comparable, since they work with different particles, materials or loads [15,23–25]. One major problem is introducing and keeping the third-body particles between the bearing surfaces [16]. To prevent sedimentation of the particles on the floor of the testing chambers, contaminated lubricants or roller pumps were used [24–27]. All studies show an increase in abrasion [15,24,27]. Some studies provide only

* Corresponding author.
E-mail address: jessica.hembus@med.uni-rostock.de (J. Hembus).

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limited information about how and where exactly the third-body particles were introduced into the artificial hip joint. In the present study, therefore, the application of these particles and its influence on the test results shall be elaborated upon. Furthermore, abrasion behaviour of ion-treated CoCr heads under third-body conditions has not been investigated so far.

Hence, the aim of the present study was to measure the amount of wear of cross-linked polyethylene inserts under third-body conditions, i.e. bone cement containing zirconium dioxide was added to the articulating surface with ion-treated CoCr as well as to that with Al_2O_3 ceramic femoral heads.

2. Material and methods

2.1. Test specimens

For the wear test, Trident® PSL uncemented acetabular cups (Stryker GmbH & Co. KG, Duisburg, Germany) were used. Acetabular cups with an outer diameter of 56 mm and suitable sequentially cross-linked polyethylene inserts were combined with 36 mm femoral heads made of ceramic (Alumina Ceramic C-Taper Femoral Head) and nitrogen ion-treated Co28Cr6Mo (LFIT™ Anatomic C-Taper Femoral Head). The polyethylene inserts (Trident® X3®) were sequentially cross-linked with compression-moulded resin sheets out of GUR 1020 by irradiating with 3 MRads, followed by annealing the components below the melting point. The process of irradiating and annealing was repeated three times [28]. The inserts were pre-soaked in the test fluid bovine serum (Biochrom GmbH, Berlin, Germany) with a protein concentration of 30 g/l, ethylene diamine tetra acetic acid (EDTA) and sodium azide (NaN_3), for eight weeks. The implants used and their respective quantity are shown in Fig. 1.

2.2. Hip simulator test and wear measurement

The wear tests were performed in a standard hip simulator (Endolab GmbH, Rosenheim, Germany) using three dynamic stations for each material combination, and one additional axial loaded soak control in order to validate the liquid absorption of the inserts. The soak control is loaded only statically with the axial load of the ISO standard. The change of the weight is only due to the fluid absorption from the lubricant of the insert. No wear occurs to the soak controls. The recorded saturation of the fluid is subtracted from the gravimetric measurement of the dynamically loaded inserts. Hence, the weight loss of the dynamically loaded inserts is only caused by abrasive wear. The loading and motion were applied on the test inserts according to ISO 14242-1 (2014) [29]. The standard defines the kinematics of the hip joint during normal gait, containing axial loading between 0.3 and 3 kN and movements of extension/flexion between − 18° and 25°, of abduction/adduction/ between − 4° and 7° and of external and internal rotation between − 10° and 2°. As described in the standard [29], the samples were articulated in bovine lubricant with a protein content of 30 g/l for 5×10^6 cycles at a frequency of 1 Hz and in temperature controlled (37 ± 2 °C) chambers. Every 500,000 cycles, the lubricant was changed and the wear of the inserts was gravimetrically detected with a high precision balance (Sartorius ME235S, Sartorius AG, Göttingen, Germany) according to ISO 14242-2 (2016) [30]. Along with the measured weight of wear and the density of the sequentially cross-linked polyethylene (0.9392 g/cm^3 [28]), the volumetric wear of the insert was also calculated. The test implants were changed periodically between the running stations to prevent station-conditioned influences.

In contrast to the standard test conditions described in ISO 14242-1 [29], in this study, third-body particles of bone cement were added to the articulating surface. Sedimentation of the third-bodies was prevented by slight indentation into the liner before wear testing. The results of this study were compared with the wear rates determined by our previous study [13], in which the same implants were tested under standard test conditions without third-body particles.

2.3. Third-body wear particles

The third-body wear particles used, were made of bone cement PalacosR® (Heraeus Medical GmbH, Wehrheim, Germany), which consists of 84.5% methylmethacrylate copolymer, 0.5% benzoylperoxide and 15% zirconium dioxide [31]. For manufacturing the particles, the liquid and the powder components were mixed and spread out thinly at room temperature. After 10 min, the bone cement was completely polymerised and subsequently smashed for one minute in an oscillating mill (MM2; Retsch GmbH, Haan, Germany). To get the desired particle size of 100–200 µm, the resulting powder was sifted through two metal grids with 0.1 mm and 0.2 mm mesh openings. This range of particle size was chosen in accordance with the studies of Grupp et al. [15] and Affatato et al. [25]. Finally, the particle sizes were verified with a laser scanning microscope (LSM VK-X250, Keyence Deutschland GmbH, Neu-Isenburg, Germany). Furthermore, investigations with energy dispersive X-ray spectroscopy (Fig. 2) proved that no metallic wear particles of the oscillating mill were mixed with the bone cement ones (Field Emission Scanning Electron Microscope Merlin V compact; Carl Zeiss AG, Oberkochen, Germany).

According to Grupp et al. [15], a particle concentration of 5 g/l was added to each testing cycle, leading to a total weight of 1.75 g of third-bodies in each 350 ml testing chamber, as determined with a high precision balance (Sartorius ME235S, Sartorius AG, Goettingen,

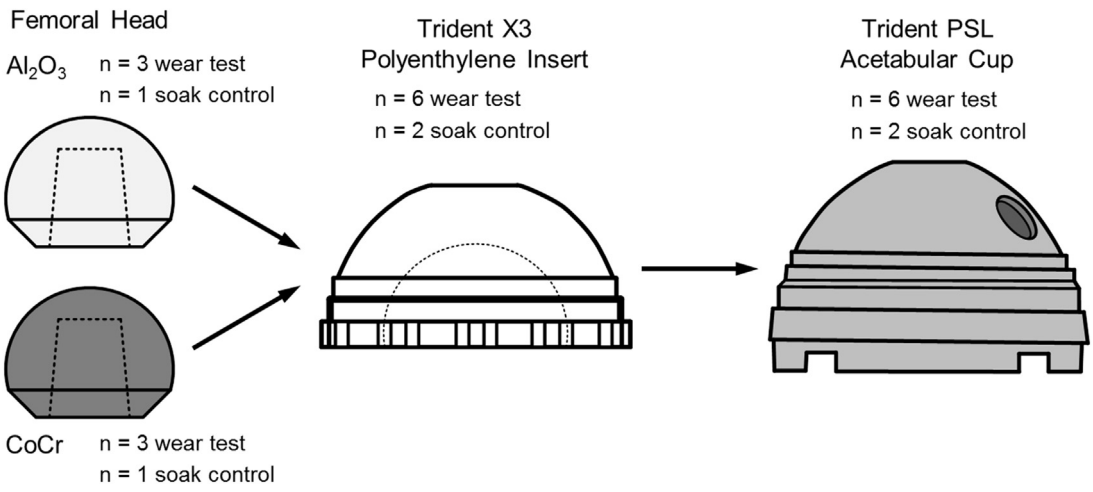

Fig. 1. Implant components used for hip simulator test.