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Polyethylene wear in primary knee arthroplasty

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Abstract Polyethylene (PE) wear is a focal issue in joint replacement, so it is essential to understand how it takes place in vivo. PE wear is a multifactorial process with a complex interaction of variables related to the materials used, the mechanical conditions, operative procedures for implantation, activity of the patient and use of prosthesis. We retrieved 65 PE inserts with the respective femoral and tibial components (50 inserts of total knee prostheses and 15 monocompartmental prostheses) from first revision surgeries. The average age of the patients was 68.3 years; the average time to revision was 41.5 months. Macroscopic observation considered the grade, topography and type of wear. Degradation was also studied with scanning electron microscopy. No direct relationship was found between the level of wear and the survival of total or monocompartmental knee prostheses. The duration of 11 (22%) total prosthetic inserts with grade 2 wear was 42.6 months vs. 51.5 months of 17 (34%) total inserts with grade 1 wear. However, study of the relationship between wear grade and wear topography in total inserts suggested that there was a significant connection. In fact, the 22 (44%) prostheses with central and symmetrical wear never showed wear greater than grade 1. Instead, of the remaining 28 prostheses (56%) without central and symmetric wear, only 3 had grade 0 wear. Finally, considering the relationship between wear grade and type of wear, all 18 inserts (27.7%) with grade 2 or 3 wear had 100% delamination. In conclusion, this study suggests that the correct positioning of the prosthetic components, besides its quality, is an important cause of polyethylene wear.

Key words Arthroplasty • Polyethylene wear • Wear topography

Introduction

Polyethylene (PE) could be considered an ideal material in total knee replacement for its excellent mechanical and physical properties, in particular for its high resistance to abrasion, very high wear-resistance and its very good biocompatibility. PE is a polymeric material made by polymerization of ethylene, a gas derived from pyrolysis of petroleum oil. Through polymerization, the monomeric molecules of ethylene are linked in order to form the polymeric chain of polyethylene. The term of PE does not define a particular polymer, but only a peculiar chemical composition.

The main chemicophysical characteristics that describe PE are molecular mass and crystallinity [1–20]. The molecular mass is the product of the molecular mass of the structural unit (ethylene in the polymeric chain) multiplied by the degree of polymerization. Molecular mass is measured in AMU (atomic mass units). Crystallinity is defined as the ratio of weight of crystalline phase compared to the weight of the whole polymer (amorphous and crystalline phases together). Crystallinity cannot be related to the molecular mass of the polymer, but depends upon its mass per unit volume or density. It is possible to define the crystallinity of polyethylene by analyzing specific absorption coefficients. In the crystalline phase, packed macromolecules occupy a smaller space than the disorderly arranged macromolecules of the amorphous phase. Thus, the mass per unit volume is greater in the amorphous phase. The disorderly arranged chains of the amorphous phase lead to the formation of some uninterrupted free spaces into which molecules of gas, such as oxygen, can diffuse. The crystallinity of the PE used in orthopaedics is calculated as 45%–60% [1–20].

There are two classic definitions of wear [1, 2]. Wear is sometimes defined as the loss of material from surfaces in relative movement, one against the other, due to friction at contact zone. However, according to the others, wear is defined as the progressive deterioration of the moving surfaces, caused by friction in the contact zones. Both definitions point out two different phenomena, just apparently similar. We know the material does not change its chemicophysical structure but releases into the environment some of its superficial particles which have been mechanically detached. On the other hand, the material deteriorates, i.e. its chemicophysical structure changes in some manner and thus releases debris. While the first definition may perhaps better describe wear of metallic materials, the second definition is more suitable for polymeric materials.

PE wear in vivo is multifactorial with a complex interaction of many variables. In fact, there are patient-related variables, such as age and gender, that are associated with the activity of the patient and the use of the prosthesis. There are variables related to knee prosthesis, which include all aspects of the femoral and tibial implants (e.g. material used, conditions of functioning, conformity between the articulating surfaces, thickness and elastic modulus of the polyethylene). There are also variables related to the operative procedure of implantation, which include operative techniques and, especially, the initial fixation of the implants [3–8, 21].

The damage caused to PE corresponds to wear from abrasion between two bodies. In the case in which a third body is found between the prosthetic components, it corresponds to three-body wear. Third-body wear also occurs when a different material interferes with metal and PE.

The resistance to wear is proportional to the molecular weight of PE. There is a direct relationship between wear and degradation. In fact, the biodegradation usually is greater in the worn surface compared to the unworn surfaces [9]. It is well known that manufacturing processes, sterilization and mechanical stress on PE cause its degradation. The degradation consists of hemolytic scission of CC bonds in the backbone of the macromolecular chain, followed by the formation of alkyl primary radicals which, in presence of oxygen, can quickly generate peroxy radicals. This last process, called oxidation, decreases the molecular weight of PE and, consequently, leads to a deterioration of its mechanical properties [8–11, 20].

The most used sterilization procedure is by gamma rays. Gamma rays produce an energy that exceeds the energy of the bonds which unite carbon molecules or carbon and hydrogen [12–14, 20]; this ruptures the bonds and, consequently, degrades the PE. In the same way, the energy due to mechanical stress is completely absorbed by the polymer at the articulating surface and is partially used to break chemical bonds.

The aim of the present work was to study the multifactorial causes of PE wear by analyzing the in vivo conditions that develop when PE is implanted in knee arthroplasty.

Materials and methods

Wear damage was observed on 65 PE inserts, with the respective femoral and tibial components, retrieved from first revision surgeries: 50 inserts were of total knee prostheses and 15 unicompartmental knee prostheses. The average age of the patients at explantation was 68.3 years (range, 54–81 years). The average lifetime of the implant was 41.5 months (range, 1–100 months).

Macrostructural evaluation and scanning electron microscopy were performed to study the wear phenomenon. At macroscopic evaluation we considered:

- The grade of wear. The inserts were measured in areas of maximum wear with a caliber. In order to evaluate the grade, we used a scale of increasing values from 0 to 3, where zero is no wear (wear less than 1 mm), one is wear up to 50% of thickness, two is wear from 50% to 100% of thickness, and three is break of the PE insert.
- Topography of wear. We considered as a mechanical optimum condition the central and symmetric wear, while nonsymmetric wear (posterior, rotatory) was considered mechanically unstable situations.
- Type of wear. Hood et al.'s classification [19] was used to evaluate the type of wear as: pitting, burnishing, third-body wear, surface deformation, abrasion, scratching and delamination. We also summarized this classification into a scale that was simpler and more easily evaluated: (1) pitting; (2) burnishing; (3) delamination; (4) mixed.

The surfaces of the inserts with the seven different types of wear were studied with scanning electron microscopy. The inserts were sectioned into small blocks with a sledge microtome and metallized with gold. The magnifications used were 25X and 50X.

We evaluated the relationship between the duration of the implant and the degree and topography of wear as well as the type and amount of wear.

Results

Wear phenomenon was studied on 65 PE inserts retrieved after first revision surgery for total knee arthroplasty (50 inserts) or unicompartmental knee arthroplasty (15 inserts). Microscopic examination revealed burnishing, pitting, scratching and delamination as the most common modes of surface damage (Fig. 1). Burnishing, or polishing, of the PE inserts (Fig. 1a) was induced by rotatory movements of the metallic component of the femur on the insert itself. Central and symmetrical polishing of PE insert indicated a correct positioning of the prosthesis with a correct soft tissues balance. Asymmetric wear, mostly posterior or anterior, indicated a technical error in positioning of the prosthesis or in the soft tissues balance. The pitting phenomenon (Fig. 1b) typically generated voids in the articular loaded surfaces. This lesion was due to an excessive laxity of the implant that allowed piston movements of the femoral component on the PE inserts. The degradation of PE facilitated the generation of these lesions, but did not determine them. In fact, pitting was not observed in the unloaded zones. The surface deformation phenomenon (Fig. 1c), also known as cold flow, led to subsequent fracture of the posteromedial corner of PE insert generated by continuous mechanic injury; most of the times this was due to lack of external rotation of the femoral component in the presence of a nonanatomical 90° cut of the tibial component. This term has been used to describe evidence of permanent deformation occurring

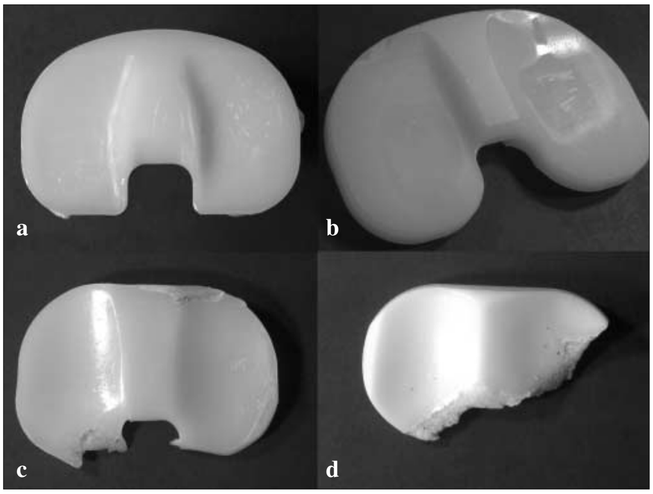

Fig. 1a-d *Four common types of polyethylene (PE) wear of knee prosthetic inserts.* **a** Burnishing, with typical areas that appear highly polished. In this case, the wear is central and symmetric. **b** Pitting, with typical voids occurring in the articulating surface. **c** Delamination, with subsequent fracture of the posteromedial corner of PE insert provoked by continuous mechanic injury. **d** The third-body wear phenomenon. The inclusion fragments are metallic. Note the cold flow deformation in posteromedial corner of the PE insert

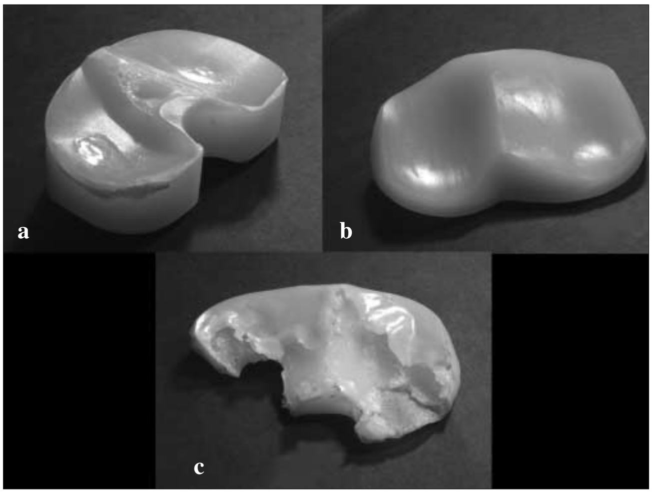

Fig. 2a-c *Examples of PE wear.* **a** Abrasion phenomenon provoked by two surfaces with different degrees of hardness. The PE appearance is typically shredded. **b** Scratching. The scratches followed the dominant direction of movement. **c** Delamination is the most serious PE injury and indicates a serious state of degradation

on or around the articular surface. Finally, metallic inclusion (Fig. 1d) was also noted in the PE inserts. The inclusions, made of cement, bone, beads, or other material harder than PE, transform the abrasion wear between two bodies to three-body wear. This phenomenon led to the formation of PE residue.

Other examples of PE wear are shown in Fig. 2. Abrasion (Fig. 2a) caused by two surfaces with different degrees of hardness caused a shredded or tufted appearance, attributed to direct sliding contact with either bone or polymethyl methacrylate. Scratches (Fig. 2b) were probably induced by the presence of small third bodies harder than PE. Rotatory or rotatory-translation movements of the femoral component on the plate caused the scratches in the areas under load. The direction of the scratches was that of rotation. The delamination in Fig. 2c was the expression of a serious state of PE degradation. We have never observed a PE insert which presented a central and symmetrical delamination. The worst state of wear always presented asymmetrical wear topography, expression of technical error in the prosthesis implant.

Scanning electron microscopy examination of PE inserts (Fig. 3) allowed us to describe more accurately the different types of wear. In PE inserts with burnishing wear, the surface appeared smooth even under microscopic observation (Fig. 3a). The pitting phenomenon generated what seems to be tapping-like lesions (Fig. 3b). The mechanism of action was not clear, but considering the topography of the lesion, the wear was probably mechanical, like a piston movement of the femoral component of the inserts. In the case of delamination, there was complete

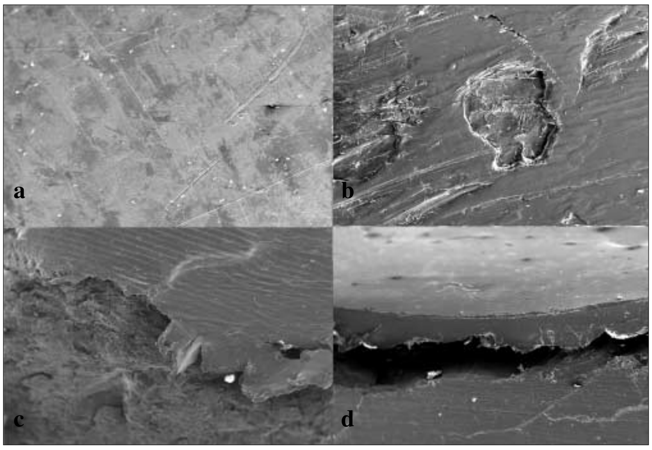

Fig. 3a-d *Scanning electron microscopy of worn PE inserts.* **a** Inserts with burnishing. The surface appears smooth even under microscopic observation. **b** Pitting phenomenon with typical tapping-like lesions. **c** Delamination with complete subversion of the structure. A single plane is no longer observed, but instead microscopy reveals a structure composed of many foils which have separated from one another. **d** Delamination phenomenon in transverse section. The peeling-off phenomenon of the superficial stratum from deeper strata is observed

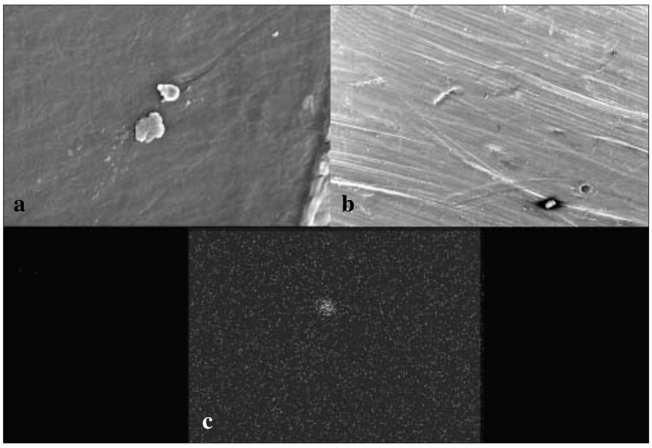

Fig. 4a-c *Other examples of PE wear.* **a** An inclusion, third-body wear phenomenon. The inclusion is calcium, presumably calcium stearate used in the extrusion of polyethylene bars. **b** The scratching phenomenon. The furrows are mostly directed along a unique axis which is that of rotation. Note also the small metal third body. **c** Mapping of calcium stearate. The *white dots* correspond to calcium

derangement of the structure. A single plane was no longer observed, and we found a structure composed by many foils which have separated from one another. When the delamination phenomenon was observed in transverse section (Fig. 3d), the peeling-off phenomenon of the superficial stratum from deeper strata was observed.

Figure 4a shows an inclusion, third-body wear phenomenon. The inclusion body was calcium, presumably calcium stearate used in the extrusion of polyethylene bars. In Fig. 4b the scratching phenomenon is observed. The furrows were mostly directed along a unique axis which was that of rotation. Finally, Fig. 4c shows mapping of calcium stearate. The white dots correspond to calcium. The maximum concentration of white dots was at the foreign body. Under molecular analysis, phosphate was not observed and hence the foreign body was not likely bone.

Considering the relationship between wear grade and survival of total knee prostheses (Fig. 5a), inserts with grade 2 wear had a mean duration of 42.6 months vs. 26.8 months for those with grade 0 wear. This means that there was no direct relationship between wear grade and

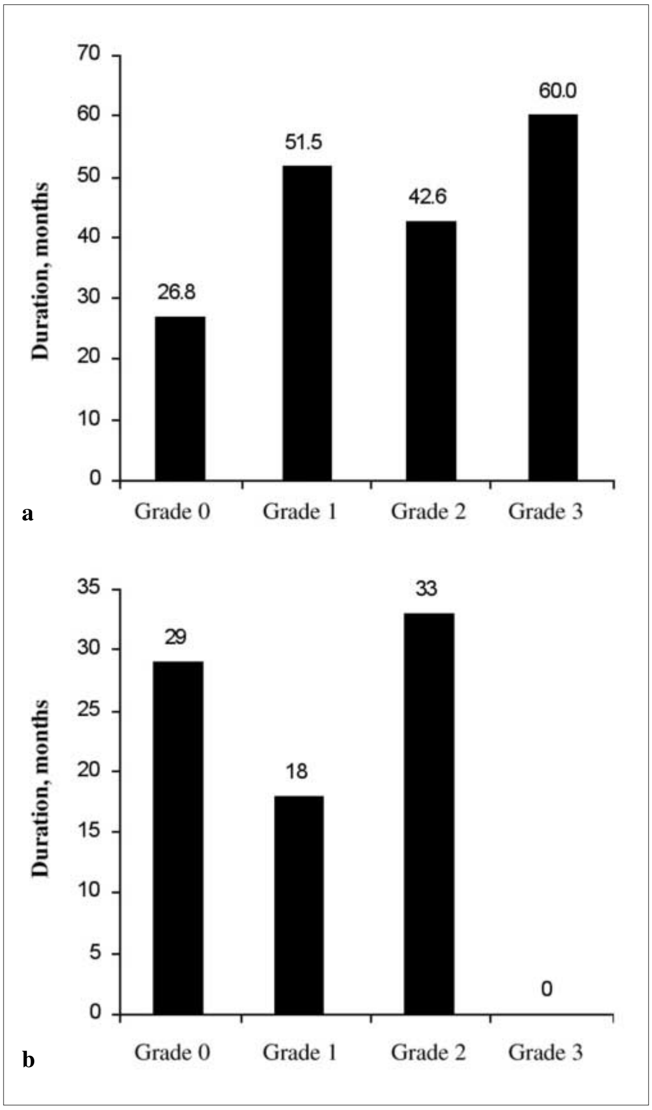

Fig. 5a, b *Relationship between wear grade and survival of knee prostheses.* **a** Total knee prostheses. **b** Monocompartmental prostheses

Table 1 Relationship between wear grade and topography, by type of prosthesis. Grades of wear were defined as: 0, no wear or wear <1 mm; wear 1, wear up to 50% of thickness; 2, wear from 50% to 100% of thickness; 3, break of polyethylene insert. Value are numbers of prostheses

	Topography		
	Central	Posterior	Rotatory
Total knee prostheses, n=50			
Grade 0	16	0	3
Grade 1	6	5	6
Grade 2	0	9	2
Grade 3	0	3	0
Monocompartmental prostheses, n=15			
Grade 0	3	0	0
Grade 1	5	3	0
Grade 2	0	4	0
Grade 3	0	0	0
All prostheses	30	24	11

Table 2 Relationship between wear grade and wear type, by type of prosthesis. Values are numbers of prostheses

	Wear type			
	Burnishing	Pitting	Delamination	Mixed
Total knee prostheses, n=50				
Grade 0	6	0	0	13
Grade 1	0	0	12	5
Grade 2	0	0	11	0
Grade 3	0	0	3	0
Monocompartmental prostheses, n=15				
Grade 0	1	0	0	2
Grade 1	1	0	4	3
Grade 2	0	0	4	0
Grade 3	0	0	0	0
All prostheses	8	0	34	23

survival of knee prostheses (but that wear grade depended more on the correct positioning of the prosthetis components). Identical observations were made for monocompartmental prostheses (Fig. 5b).

Considering the relationship between wear grade and topography for total knee prostheses (Table 1), 22 (44%) of 50 inserts with central and symmetrical wear never showed wear greater than grade 1. The remaining 28 (56%) prostheses without central and symmetrical wear had grade 0 wear only in 3 cases (6%), grade 1 wear in 11 (22%) cases, and grade 2 wear in 11 (22%) cases; there were 3 cases (6%) of breaking (grade 3). A direct relationship between wear grade and asymmetry of wear was not detected because of the small number of cases, but the topography of wear seemed to be a crucial factor to take in account in the analysis of knee arthroplasty failure. The same evidence was obtained for monocompartmental prostheses (Table 1).

Considering the relationship between wear grade and type of wear (Table 2), all total knee protheses with grade 2 or 3 wear had delamination wear only. Thus, higher the grade of wear, the degree of wear was also greater. The same observations were made for monocompartmental prostheses.

Discussion

Many authors have reported on the causes of PE wear, focusing only on issues related to the manufacturing process and sterilization [1, 2, 6, 9, 10, 12, 16, 18, 20]. We must be careful about this tendency. As PE wear is a focal issue in joint replacement, it is essential that we realize the complexities of all variables that cause wear in vivo. This study presents a comprehensive review of 65 retrieved PE inserts.

PE wear is certainly a multifactorial process including the conformity between the metallic and PE articulating surfaces, the thickness of PE, the elastic modulus of the PE materials and the physical properties of the PE that can be changed by fabrication technique, sterilization and degradation in vivo. However, the correct positioning of the prosthetic components seems to play an important role in knee arthroplasty failure. In fact, our study revealed a relationship between wear grade and wear topography, showing that central wear was not present in PE inserts with wear greater than grade 1. Therefore, poor positioning of the prosthetic components and improper soft tissue balancing, even without a specific problem of PE, leads to an inevitable failure. On the other hand, good balancing of the prosthetic components even with some wear of PE allows a long-lasting implant. In conclusion, matching a good balance and a good PE insert gives the best chances to have the overall best results.

No relationship between wear grade and survival of knee prostheses was found in our study, underling the multifactorial origin of knee arthroplasty failure.

Remarkably all the retrieved inserts with wear grades greater than one showed the presence of delamination. We believe that highly oxidated PE is more prone to severe degradation and this is probably the reason for these findings.

Unfortunately most of the retrieved inserts came from implants removed for mechanical failure and, only a few, for infection. The findings could be different for inserts of well functioning implants removed at autopsy. Future plans include extending the study to inserts of well functioning implants.

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