U.PORTO
INSTITUTO DE CIÊNCIAS BIOMÉDICAS ABEL SALAZAR
UNIVERSIDADE DO PORTO

Artigo de Revisão Bibliográfica
Mestrado Integrado em Medicina

# HIP OSTEOARTHRITIS – TOTAL HIP ARTHROPLASTY

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Junho/2010

# Agradecimentos:

**Joana Aguiar**

## Abstract

Osteoarthritis is a major source of disability in people aged 65 and older. Currently, Total Hip Arthroplasty is the best available option for pain reduction and restoration of functional ambulation, as well as for a wide variety of joint pathologies. It is one of the most frequent elective surgical procedures done all over the globe with an ever growing number of surgeries performed every year. Patients who are younger or active, or both, and require total joint replacement pose a unique challenge; their high activity levels require wear-resistant bearings that will perform for decades, without suffering from the undesirable effects of accumulated wear products. Therefore, new materials have been studied and used clinically in an attempt to achieve these goals. This bibliographic revision intends to discuss the tribologic and biologic properties of new bearing couples and their performance *in vivo*. The new polyethylenes are projected to address the aseptic loosening problem by reducing the volume of submicron polyethylene particles to a level well below the documented threshold for osteolysis. Nonetheless, deciding between the numerous variations of the cross-linked thermally-stabilized polyethylenes is confounded by contradictory opinions concerning the optimal equilibrium between long-term wear resistance and mechanical strength, and regarding possible effects of the submicron-sized wear particles on their relative osteolytic potential. Metal-on-metal bearings have clinically proven wear resistance, the advantage of self-polishing, and they allowed for the reintroduction of the resurfacing arthroplasty, but the long term biologic effects of metallic ions remain largely unknown. Ceramic-on-ceramic bearings have the advantage of high biocompatibility and usually very low wear, but fracture remains a rare but catastrophic complication. The selection of a suitable bearing couple should be made after a careful contemplation of the relative risks and potential benefits of each of these materials.

## Keywords

Osteoarthritis, total hip arthroplasty, polyethylene, ceramic-on-ceramic, metal-on-metal, wear.

## List of Symbols

| | |
|---|---|
| AMC | Alumina Matrix Composite |
| Co | Cobalt |
| Cr | Chromium |
| FDA | Food and Drug Administration |
| OA | Osteoarthritis |
| PE | Polyethylene |
| RHA | Resurfacing Hip Arthroplasty |
| ROM | Range of Motion |
| TCR | Tribochemical Reaction |
| THA | Total Hip Arthroplasty |
| THR | Total Hip Replacement |
| Ti | Titanium |
| UHMWPE | Ultrahigh Molecular Weight Polyethylene |

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## I - Introduction

Osteoarthritis (OA) is primarily a noninflammatory disorder of movable joints characterized by an imbalance between the synthesis and degradation of the articular cartilage, leading to the characteristic pathologic changes of wearing away and destruction of cartilage. It is a chronic irreversible degenerative disease. OA was formerly thought to be a normal outcome of aging, thus leading to the term degenerative joint disease. However, it is now known that osteoarthritis results from an intricate interaction of numerous factors. Though several non-surgical treatments are available for the patients with this disease, surgery is still the only curative treatment available [42].

Total hip arthroplasty (THA) is the surgical reconstruction or replacement of a malformed, degenerated or traumatized hip and is one of the most successful and cost-effective surgical interventions introduced in medicine during the last 80 years. It is one of the most frequent elective surgical procedures with an estimate of one million artificial hips implanted worldwide every year [46]. Because of an aging population and the extension of the procedure to younger patients, technological and surgical aspects of joint replacement are constantly reviewed and improved.

This bibliographic revision intends to analyze and compare the different materials available for total hip replacement in osteoarthritis patients.

## II - Materials and Methods

For this bibliographic revision, a database search for publications on osteoarthritis and total hip arthroplasty studies was performed. The PubMed database (U.S. National Library of Medicine and the National Institutes of Health) and the *b-on* (Biblioteca do Conhecimento on-line) search engine were searched for words and phrases, including osteoarthritis, hip, total hip arthroplasty, polyethylene, metal, and ceramic. Studies that were referenced in these databases were also included.

Criteria for inclusion were somewhat subjective but based on assigned rank, relevance, and year of publication.

Additionally, orthopaedics manuals were consulted for information concerning definition, classification, epidemiology, pathophysiology, and diagnostic criteria for osteoarthritis.

# III – Osteoarthritis

## 1 - Classification

Osteoarthritis (OA) has conventionally been classified according to etiology into either idiopathic or secondary. The idiopathic form of the disease is categorized into localized or generalized. Localized OA most commonly affects the hands, feet, knees, hips, and spine. Generalized OA is characterized by the involvement of three or more joint sites. Secondary OA ensues from specific conditions that may cause or enhance one's risk to develop OA, including trauma, rheumatoid arthritis, gouty arthritis, congenital or developmental disorders, diabetes mellitus, hypothyroidism, and neuropathic arthropathy [45].

Osteoarthritis may also be classified by anatomic involvement, which includes the site of chief joint involvement, the number of joints implicated, and the presence of specific features such as inflammation or erosion [45].

## 2 - Epidemiology

Osteoarthritis has a high incidence in developed countries. With the aging of the population and the increasing life expectancy, its prevalence is expected to rise drastically in the next decades. OA is second only to ischemic heart disease as a cause of work disability in men over age 50 and is a major source of disability in people aged 65 and older [44]. The reported prevalence of OA varies according to the method used to detect it. X-rays are the most commonly used means of diagnostic. However, its low sensitivity deems necessary for severe osteoarthritic damage to be present so characteristic changes can be observed with this technique. Hence, more subtle alterations may not be detected with this exam. Radiographic changes are seen in over half of those aged 65 or older with OA of the knee. In contrast, autopsy studies show that there is almost universal evidence of osteoarthritic damage in this age group [29][35].

## 3 - Risk Factors

Several risk factors are associated with OA. Its incidence is known to increase with age and body mass index. Gender has some influence on the distribution of the disease, with knee and hand arthritis being more common in women whereas hip involvement is more common amongst men. Genetic factors seem to have a role in one's susceptibility to OA, especially when the hand and hip joints are involved. Even though the genes responsible for this are still unidentified, it's known that chromosomes 2 and 11 may play a role in the development of this disease [7]. The absence of osteoporosis, occupation, sports activities, previous injury, muscle weakness, proprioceptive deficits, acromegaly, and calcium crystal deposition disease are some of the remaining risk factors commonly associated with OA [33].

## 4 - Pathophysiology

Even though the term "osteoarthritis" implies an inflammatory process, in most cases, OA is considered to be an intrinsic disease of the articular cartilage in which biochemical and metabolic alterations result in its collapse [33].

In normal, adult articular cartilage, extracellular matrix is constantly being degraded and repaired. However, when compared with other connective tissues, turnover is slow and the capacity of repair is limited. These two processes of degradation and repair are generally kept in balance by the activity of the chondrocytes which, in turn, are under the influence of several biomessengers, such as interleukins, insulin-like growth factor-1 (IGF-1) and transforming growth factor beta (TGF-beta). This equilibrium can be disrupted by a myriad of factors. The more important ones are, probably, aging and mechanical effects. Despite the fact that OA is not a process exclusively of wear-rupture, there is little doubt that mechanical stresses have a leading role in its development. Evidence to support this conclusion includes the high incidence of OA amongst the elderly, the involvement of weight-bearing articulations and the increase in OA' frequency associated with conditions that predispose the articulations to abnormal mechanical stresses, such as obesity and previous articular deformity [33].

OA is characterized by significant alterations in the composition and in the mechanical properties of cartilage. In an initial phase, chondrocytes proliferate and, consequently, bioquemical alterations such as an increase in the matrix water component and a decrease in proteoglycan concentration ensue, which provokes losses in the glistening appearance of the articular cartilage. Later on, the superficial layers flake off while deeper layers develop longitudinal fissures, a process termed fibrillation. As the collagen fiber structure is altered and the number and quality of proteoglycan aggregates decreases, cartilage becomes thin and sometimes denuded. The subchondral bone becomes thickened, sclerotic, and polished (eburnation); it displays thickened trabeculae and microfractures. Cysts may be seen in subchondral bone which arise from increases in intrasynovial pressure. Spurlike bony outgrowths covered by hyaline cartilage (osteophytes) may develop at the margins of the joints and progressively enlarge. Small bits of cartilage-covered bone, known as joint mice, may actually break off into the joint. With the progression of the disease, the synovium becomes hypertrophied and thrown into villose folds. Infiltration with plasma cells and lymphocytes may be seen. The synovial hypertrophy may be involved in provoking joint pain by increased synovial fluid production and increased intra-articular pressure [33].

## 5 - Diagnosis

The symptoms' onset is insidious. Patients with an idiopathic form of OA seldom present any symptoms before the end of their fifth decade of life. The initial manifestation may be articular stiffness, rarely lasting more than 15 minutes; later on, the patient develops pain on motion of the affected joint that is worsened by activity or weight bearing and relieved by rest. Bony enlargement of the distal interphalangeal (DIP) (Heberden's nodes) and proximal interphalangeal (PIP) (Bouchard's nodes) joints are occasionally prominent, and flexion contracture or varus deformity of the knee is not unusual. There is no ankylosis, but limitation of motion of the affected joint or joints is common. Crepitus may often be felt in the joint. Joint effusion and other articular signs of inflammation are mild. In the idiopathic form of the disease there are no systemic manifestations [45].

Plain radiographs of the affected joint can both help to confirm a diagnosis of OA and to grade its severity. Results of routine laboratory tests are normal and are, therefore, only useful in screening for associated conditions and for establishing a baseline for monitoring therapy [45].

## 6 - Hip Osteoarthritis

The natural history of hip OA is extremely variable. Most patients experience relatively mild symptoms over prolonged periods, whereas a few appear to "recover" spontaneously. Yet others manifest a rapidly progressing OA that often leads to surgery. Occasionally, frank joint destruction occurs, which may lead to severe pain and disability [11].

Hip OA affects slightly more men than women; fact that is possibly due to hip loading. The most common risk factors for secondary OA of the hip are congenital dislocation or dysplasia of the hip, Legg-Calvé-Perthes disease, Paget disease, a slipped capital femoral epiphysis, traumatic dislocation, fracture of the acetabulum and haemophilia [12].

The most prominent manifestation of hip OA is pain with walking. This pain may be referred to the buttocks, groin, thigh, or knee, complicating the diagnosis. Several activities may be compromised by this condition, such as bending to put on socks or shoes or sexual difficulties because of painful hip motion. As for other articulations, signs and symptoms include pain, inactivity stiffness, crepitus, and reduced range of motion [45].

The heterogeneity of OA has led to attempts to establish diagnostic criteria for the disorder at the most commonly affected sites (i.e., the hand, hip, knee, etc). According to the most widely used criteria developed by the American College of Rheumatology (ACR) [4] the major criteria for diagnosis of OA is joint pain for most days of the month. This is contrasted to radiographic criteria, in which many patients do not report joint pain. For hip OA, the ACR's criteria rely on the presence of hip pain plus any two of the following features:

- erythrocyte sedimentation rate < 20mm/hour
- radiographic femoral or acetabular osteophytes
- radiographic joint space narrowing (superior, axial, and /or medial)

This criteria yield a sensitivity of 89% and a specificity of 91%.

## 7 - Treatment

Since OA is an irreversible process, there is no drug or physical treatment capable of repairing the damaged cartilage.

The treatments currently available can be divided into surgical and non-surgical. The latter is composed of pharmacologic and nonpharmacologic therapies.

The main objectives of the pharmacologic therapies are the control of pain and swelling, to minimize disability, and improve quality of life. For this, analgesics, such as acetaminophen and opioids, nonsteroidal anti-inflammatory drugs, intra-articular glucocorticoids [32], intra-articular hyaluronans and colchicine are used. Antimalarial drugs, tetracyclines, diacerein, counter-irritants and rubefacients, and modulators of cartilage constituents (e.g. glycosaminoglycans) are treatments under investigation.

In the nonpharmacologic approach, behavioral changes, such as weight loss and dietary changes, plus physical therapy and orthoses, transcutaneous electrical nerve stimulation (TENS) and temperature-based therapies, constitute the available options [1][41].

The surgical treatments for OA are, without a doubt, one of the most flourishing areas in medicine. Every year the number of surgeries performed increases and, with the expected raise in OA' prevalence, the pressure for improvements in technique and materials is mirrored by the increase in the number of studies and publications on this issue [6].

Surgical interventions for patients with OA are generally reserved for those who have failed less invasive modes of therapy. This means that, usually, surgery is performed in patients with more severe compromise of their articular cartilage, whether it resulted from a long period of disease or a rapidly progressive form of OA [45].

Nowadays, the reference surgery for OA of the hip is the Total Hip Arthroplasty (THA), also known as Total Hip Replacement (THR). The modern era of successful THA replacement began in the mid-1960s with the introduction of total hip replacements, particularly by McKee and Farrar, which featured a metal-on-metal bearing, and the Charnley, featuring a metal-ball-on-Teflon socket, later replaced by a metal-ball-on-polyethylene due to early failure of the acetabular component. The clinical success of the latter quickly led to the introduction of replacements for other joints using metal-on-polyethylene and, subsequently, ceramic-on-polyethylene bearings, including knee, ankle, shoulder, elbow and, more recently, spinal disks [40]. At present, the success rates of THA at 10 years or longer exceeds 95% survivorship in patients older than 75 years. These patients are expected to sustain a higher level of activity. In addition, life expectancy has increased, which has placed an increasing demand on these arthroplasties. For these reasons, even though this is a highly successful operation, the number of revision procedures is expected to increase in the near future and the pressure to develop new, more resistant and less prone to failure materials is at its peak [48].

When total joint arthroplasty was first introduced, patients older than 65 years were considered the best candidates for the procedure. More recently, however, there has been a steady increase in the number of patients younger than 60 years undergoing THA. Regrettably, the survival rate for hip prostheses decreases significantly with the patient's age, presumably because of increased activity and, consequently, higher wear rates of the implants. According to current knowledge of the process of particle induced osteolysis, reducing the volume of wear particles produced by THA implants should decrease the undesirable biologic reaction to them. The reintroduction of alternative bearings such as metal-on-metal, ceramic-on-ceramic, and ultrahigh molecular weight polyethylene (UHMWPE) with elevated cross-linking may represent a great advance towards this goal, particularly for the younger and/or more active patients who have been subject to a high incidence of osteolysis with the historic air-irradiated polyethylene [10].

## IV - Ultrahigh Molecular Weight Polyethylenes

Total hip arthroplasty with the use of traditional metal-on-polyethylene bearing couples has been demonstrated to improve function and eliminate pain in patients with severe OA. Despite this overall clinical triumph, the clinical life span of total hip prosthesis often has been narrowed by osteolysis and, in some cases, aseptic loosening brought on by the macrophage reaction to wear particles. Osteolysis secondary to polyethylene wear has been described as one of the main reasons for late revision of THA [8]. It follows that improving the wear resistance of the polyethylene could contribute to greater durability of hip prostheses.

Since wear-related osteolysis was first recognized as a cause of revision, other bearing couples have been developed in an effort to reduce particle generation. In the 1990s, a number of highly cross-linked polyethylenes were developed as an approach to reduce wear of total hip prostheses and, potentially, to increase implant longevity. Laboratory wear testing of the highly cross-linked polyethylenes in hip joint simulators confirmed dramatically improved wear resistance, with many investigators reporting reductions in wear of more than 90% even under unfavorable circumstances [28]. The research for the amount of radiation more effective in decreasing wear rates demonstrated that the quicker decrease in wear rate commonly occurs as the cross-linking dose is increased from 0 to about 5 Mrad, with wear becoming too small to accurately determine between 10 and 15 Mrads. However, excessively high cross-linking may diminish the fatigue strength and fracture toughness of the polyethylene (PE) below that required to avoid fracture of the components *in vivo*. Since the majority of existing data concerns the prostheses cross-linked at the moderate level (2,5 to 4 Mrads) of gamma radiation used for sterilization and fracture *in vivo* being an uncommon phenomenon, with the fractured components characteristically presenting as highly oxidized, it stands to reason that the strength and toughness of a PE component that has a moderate amount of deliberate cross-linking and has been rendered immune to postirradiation oxidative degradation by the use of an adequate thermal treatment to eradicate free radicals, should be more than sufficient even for high-stress clinical applications [10].

Currently, the prostheses being commercialized are subjected to an overall radiation between 5 and 11 Mrads (**Table 1.**).

**Table 1.** Comparison Among Cross-Linked Thermally-Stabilized Polyethylenes

| Name and Manufacturer | Radiation Type and Dose | Thermal Stabilization | Final Sterilization | Total Cross-Linking Dose and Type |
|---|---|---|---|---|
| Marathon™ DePuy, Inc | Gamma radiation to 5 Mrads at room temperature | Remelted at 155°C for 24 hours | Gas Plasma | 5 Mrads gamma |
| Longevity™ Zimmer, Inc | Electron beam radiation to 10 Mrads at warm room temperature | Remelted at 150°C for approximately 6 hours | Gas Plasma | 10 Mrads electron beam |
| Durasul™ Sulzer, Inc | Electron beam radiation to 9.5 Mrads at 125°C | Remelted at 150°C for approximately 2 hours | Ethylene oxide | 9.5 Mrads electron beam |
| Crossfire™ Stryker-Osteonics-Howmedica, Inc | Gamma radiation to 7.5 Mrads at room temperature | Annealed at about 120°C for a proprietary duration | Gamma at 2.5 to 3.5 Mrads while packaged in nitrogen | 10 to 11 Mrads of gamma |

(The processing parameters shown in this table were compiled from various publications, and information provided by the manufacturers and are subject to ongoing modification.)

(Modified from McKellop HA: Bearing Surfaces in Total Hip Replacements: State of the Art and Future Developments. In Sim FH (ed). Instructional Course Lectures. Rosemont IL, American Academy of Orthopaedic Surgeons 165-179, 2001.) [39]

If it is an undisputable truth that excessive polyethylene wear can lead to late failures as a result of several different mechanisms, the most frequent being osteolysis and aseptic loosening, it is now known that the size and shape of the particles created by wear plays a decisive role in the chain of events leading to clinical failure of the PE components. Some studies have compared the osteolytic activities of different types of PE debris. For example, Matthews and colleagues [10] incubated wear particles from a noncross-linked PE with monocytes taken from healthy human subjects and found that particles in the size range of 0.24 ± 0.094 μm induced an osteolytic reaction at a lower concentration than particles in the ranges of 0.42 ± 0.22 or 1.7 ± 0.99 μm. Holley and colleagues [28] used a hip simulator to compare the wear behaviors of PE liners that had been cross-linked with 2.8, 10 or 20 Mrads of gamma irradiation, with the additional condition of impingement. The cups irradiated with 10 Mrads showed the lowest wear rates; however, as the test progressed, those cups apparently produced more small wear particles (approximately 0.2 μm) than did the cups irradiated with 2.8 Mrad. Another study [27] compared the long term outcome of Hylamer (a modified ultra high molecular weight PE) with a conventional PE liner. Despite the similar wear rates between the bearing surfaces, the prevalence of pelvic osteolysis with the Hylamer liner was twice that of the conventional PE liner; and the estimated area of pelvic osteolysis was more than double that of the control group. The authors hypothesized that, since Hylamer wear particles are known to be smaller in size than conventional PE particles, the larger number of smaller wear particles from the Hylamer may stimulate a more severe biological response. This raises the concern that, despite the lower wear rates, highly cross-linked polyethylenes produce smaller particles with a lower threshold for inducing an adverse biologic response.

In order to ascertain the amount of wear taking place whether with the highly cross-linked or with the conventional PE, several studies have been conducted. A recent publication by Campbell and colleagues [8], who studied the amount of wear created by a Marathon™ acetabular liner, demonstrated that 94% of the proximal head penetration measured occurred within the first 12 months and there was negligible change in femoral head penetration between 1 and 2 years. The measurement of proximal head penetration in the study included both the initial “bedding in” of the liner into the metal shell and creep, along with the “true” wear of the PE liner; the former is generally assumed to occur during the first 12 months after the THA and is the probable responsible for the bulk of proximal head penetration occurring throughout that period. When wear rate was measured for the period subsequent to the first 12 months, it was well beneath the osteolysis threshold of 0.1 mm/year given by Dumbleton [17]. Nevertheless, Dumbleton’s conclusions were drawn from studies with conventional PE and, as stated above, lower wear rates of highly cross-linked PE may be sufficient to induce the same biologic response. In a meta-analysis by McKellop and colleagues [28], it was observed that, although the apparent wear rate of the highly cross-linked PE during the first few years of clinical use has been inferior to that of the traditional PE, the total decrease has been inferior than the percent reductions measured with prior hip-simulator wear testing; the percent reductions in the rate of femoral head penetration have ranged from 23% to 95%, depending on which traditional PE was used as a control. Once more, this difference was attributed to creep deformation occurring throughout the first 6 months of use. Since the rate of creep is not appreciably altered by the amount of cross-linking, the total penetration during the first one to two years of use tends to be similar between the two types of PE, albeit one is wearing comparatively less than the other. Consequently, in the midterm studies, when the initial phase is excluded, the percent decline in wear due to elevated cross-linking tends to be higher.

Several factors have classically been said to negatively influence clinical performance of PE components, including age, gender, body mass index, and activity level; however, neither early nor midterm clinical wear of highly cross-linked PE liners appears to be noticeably influenced by this factors. On the other hand, the factors not related to the patient seem to play a major role in the outcome of the THA. Material properties and wear characteristics resulting from the specific manufacturer differences, like gamma versus electron beam radiation or the sterilization process, are the likely accountable for the differences in wear observed between the different PE prostheses. The surgeon's experience and high volume of procedures of the hospital also seem to influence the rate of revision. Proper alignment of the acetabular component is vital to a favorable outcome regardless the PE used [28]. Finally, large femoral heads have been associated with increased wear of traditional UHMWPE liners. Nonetheless, this tendency does not seem to carry over to highly cross-linked PE liners. In a hip-simulator study comparing PE wear between nominally cross-linked PE liners (irradiated with 2.9 Mrad) and highly cross-linked PE liners (irradiated with 10.5 Mrad and annealed), Hermida *et al.* [25] reported that the highly cross-linked PE liners demonstrated a 90% reduction in wear when they were used with a 28-mm femoral head and an 85% reduction in wear when they were used with a 32-mm head. Moreover, the authors affirmed that enlarging the head dimension did not appreciably increase the wear of the highly cross-linked PE liners.

Finally, continued close monitoring of patients with highly cross-linked PE components is vital to conclude if the enhanced wear resistance that has been observed in the midterm will evolve into a considerable decline in the prevalence and severity of osteolysis after long term follow-up.

## V - Ceramic-on-Ceramic

There are many mechanical characteristics that make alumina ceramic bearings ideal in THA. Alumina is 10 times harder and zirconia seven times harder than cobalt-chrome. Alumina has a hardness of approximately 2000 VH (Vickers Hardness), compared to cobalt-chrome at 240 to 450, and other than diamond, is the hardest material available. This hardness provides for improved scratch resistance. Another key to superior wear properties is the enhanced lubrication found with ceramics due to its lower wetting angle, which is the angle formed between the material and a bead of fluid (ie, synovial fluid). This permits better wettability, especially when coupled with the formation of a microfilm of lubrication on the surface of ceramics due to the van der Waals forces between water and aluminum oxide materials. Finally, strong bonding between the oxygen and aluminum ions provides extremely good corrosion resistance, leading to better biocompatibility, and because they are inert, there is no concern about allergic reaction [36].

In 1970, Boutin initiated clinical implantation of alumina-on-alumina bearings in France [14]. Latter that decade, Mittelmeier developed and used in Europe the Autophor and Xenophor prostheses (Oslo, Selzach, Switzerland), which were introduced in the United States in the early 1980s. The initial clinical performance of alumina-on-alumina bearings that used monolithic alumina sockets was often poor and, although surgical and design factors played a role in their failure, it’s now acknowledged that the ceramic’s quality was poor by today’s standards. Failure rates as high as 13% were reported, and failed prostheses commonly experienced high wear or fracture. Additionally, the design of the initial prostheses positioned them at risk for neck-socket impingement and rapid wear. Regardless of these design and material limitations, long-term success of first-generation alumina-on-alumina bearings has been reported, and, remarkably, the incidence of osteolysis has been low [10]. With the use of today’s improved implant designs, the new ceramic coupling has a reported revision rate of 4.7% at an average of 6 years and wear rate similar to that of the metal-on-metal bearings.

Zirconia ceramic was first introduced in THA in the 1980s as a material for the femoral ball in combination with an UHMWPE acetabular component, and it seems that it has performed well in that configuration. Yet, with zirconia ceramic, the potential exists for late phase transformation and aging, resulting in grain pullout, surface cracking, and increased surface roughness. Zirconia ceramic has three phases of physical structure. The tetragonal phase has the utmost mechanical strength and is used for the production of prosthetic femoral heads, but it is also the most unstable phase with potential surface transformation back into the more stable monoclinic phase. Phase transformation can result from cyclic contact loading at pressures that are frequently found in the hip, as well as from contact with water or body fluids [15]. In one study of 52 retrieved zirconia heads, the monoclinic content within the bearing surface averaged 40% compared with 3% in nonimplanted heads [18]. Increased PE wear rates in THAs with zirconia femoral heads have been observed clinically. Longevity of THAs with zirconia heads has been questioned by a report of a poor survival rate (63%) in a series of 78 THAs with a zirconia-on-PE bearing at 5.8 years follow-up [3]. Recently, Cohn *et al* [15] reported comparable wear characteristics and rate of osteolysis amongst cobalt-chromium-on-PE and zirconia-on-PE THA and, considering the potential for deleterious phase change of zirconia femoral heads, concluded that the use of the zirconia heads in THA seems unwarranted.

Newer alumina ceramic design options have suggested enhancements of a harder, more resistant surface leading to superior tribologic properties since its low grain size assures a low surface roughness. These designs generate less debris since their high density, high purity, and small grains, have a lesser coefficient of friction, have enhanced fracture toughness, and are more hydrophilic than both PE and metal [22]. The theoretical advantages of alumina-on-alumina bearings are related to tribologic properties such as the scratch resistance and wettability of the material. In addition to superior wear properties, ceramics are biologically inert. These favorable qualities are particularly desirable for implants in a young and active population.

The second-generation ceramics were first utilized in clinical studies in the 1990s and the medium and long-term data related to their usage is currently being published. The incidence of fracture has greatly decreased and revision has reached the same level as for other bearing materials such as metal-on-polyethylene. The main concern related to these bearings is still the rate of fracture. Though relatively exceptional amongst the new prostheses, when such event occurs, it can be quite catastrophic, demanding revision and sometimes putting the new prostheses at risk. The surgeon has to make sure all the fragments are removed for their remaining may enhance wear, further the development of osteolysis, and cause extensive third-body abrasive wear if a metal femoral ball is used in the revision. Hence, manufacturers of ceramic components advocate that only ceramic balls should be used in revising broken ceramic components. Regrettably, ball fracture frequently causes substantial damage to the Morse taper, and the likelihood of fracture of a new ceramic ball is considerably higher if it is placed on a damaged taper. In such cases, the safest alternative is to substitute the entire femoral component, but this may be particularly complicated if the stem is well-fixed [10].

The third-generation ceramics alumina matrix composite (AMC) ceramic (BIOLOX™ Delta; CeramTec AG, Plochingen, Germany) consists of 82% alumina and 17% zirconia based on volume. Chromium oxide (0.5%) is added to improve the hardness and wear characteristics, and strontium crystals (0.5%) are added to augment toughness and disperse crack energy. The material has a smaller grain size (less than 0.8 μm) compared with the grain size of alumina (1-5 μm). These enhanced mechanical properties diminish overall wear rates of 28-mm heads in a simulator wear test from 1.84 $mm^3$ per million cycles to 0.16 $mm^3$ per million cycles, comparing alumina-on-alumina versus AMC-on-AMC, respectively. The enhanced mechanical properties allow for the manufacturing of thinner liners and, consequently, the use of larger femoral heads, even in smaller-diameter acetabular components. The reduced impingement, improved stability, and lower dislocation rate associated with the use of a larger femoral head diameter combined with the low wear rate would provide a major advantage to this bearing combination [23].

As stated above, ceramic-on-ceramic bearings have the apparent advantages of extremely low volumetric wear and high degrees of biocompatibility and biostability. The wear of a correctly installed alumina-on-alumina prosthesis is extremely low, and osteolysis is rare. Ceramic particles are largely insoluble in organic biologic media, and ionizing is, therefore, minimal. Also, it has been shown that the debris generated from the taper junction of the stem is considerably less when a ceramic femoral ball is used, in contrast with the use of a metallic femoral head. Nonetheless, in sufficient quantities, alumina particulate induces biologic responses similar to those induced by PE. The periprosthetic cellular response to wear particles of alumina ceramics seems to be determined by the same biologic factors that govern the response to particles of other biomaterials, that is, size, shape, and volume. Also, several studies have reported that alumina particles are not cytotoxic to fibroblast but may have some cytotoxic properties to macrophages or osteoblasts. Hence, it seems that alumina exhibits cell-specific cytotocicity [46]. Studies have shown that the particles produced by wear of the ceramic prostheses are approximately the same size as the PE particles, but the amount produced is, generally, extremely small. Consequently, it seems that the low volume of debris generated from well-functioning alumina ceramic bearings is unlikely to produce an osteolytic response, and reports of a mostly fibrotic reaction in tissues recovered from hips with low wearing alumina-on-alumina bearings support this. However, in cases where damage to the bearing surfaces has exacerbated the wear rate, the increased volume of debris may exceed the threshold for lysis, and indeed, cases of osteolysis around alumina-on-alumina bearings have been reported [2].

A more recent concern is related to the occurrence of noise (“squeak”) associated with ceramic-on-ceramic bearings. Although long-term clinical implications of squeak are unknown, the squeak phenomenon can have a psychological impact on patients, sometimes leading to decreased satisfaction or revision. Occurrence of squeak has been reported as ranging from 0.7% to as high as 20.9% [37]. Various etiologies have been suggested but none has yet been proved to be the culprit, thus, the etiology is, almost certainly, multifactorial, the result of a combination of issues ranging from hard-on-hard bearing surfaces, microseparation and subluxation associated with impingement and secondary stripe wear, entrapment of third-body wear debris, disruption of fluid film lubrication, and mismatched ceramic bearings [13][36].

A number of concerns persist, including the risk of head or liner fracture. In addition, ceramic-on-ceramic articulations are not immune to wear and surface damage. The newer ceramics have been in clinical use for only a few years, and therefore long term follow up will be necessary to determine if osteolysis has been minimized by recent advances in tribology.

## VI - Metal-on-Metal

Metal-on-metal bearings have a long history in total hip replacement. Survivorship of early metal-on-metal bearings was limited, even though many lasted more than two decades, with some still functioning in patients. Superior manufacturing methods led to reintroduction of metal-on-metal bearings and mounting interest in these implants, particularly for hip resurfacing in young and active patients [30].

The first THA used a metal-on-metal bearing. It was introduced clinically in the United States in 1966, shortly before the Charnley metal-on-PE low friction arthroplasty. Its poorer outcomes, chiefly because of poor fixation and inferior design, led them into near oblivion. Nowadays, with the mean patient age tending to decrease and, therefore, an increase in demand for long lasting prostheses, attention is, once more, directed to hard-on-hard bearings, namely to the metal ones, since some of the first-generation McKee-Farrar components are still functioning after 2 to 3 decades of use [10].

THAs with second generation metal-on-metal bearing surfaces, made of cobalt-chromium-molybdenum alloy, were introduced in 1988 and short and mid-term clinical outcome studies are now available [43]. Improvements in the manufacturing of second-generation metal-on-metal hip bearings include advanced metallurgy, and stricter tolerances in roundness, clearance, and surface roughness. Hip simulator studies and clinical evaluations have indicated wear rates for the second-generation metal-on-metal hips as low as, or lower than first-generation hips [10]. Nearly all simulator tests to date described a characteristic wear pattern for metal-on-metal bearings that is marked by an initial high running-in wear rate, which decreases to a lower steady-state wear rate during the course of the simulation. It is assumed that the behavior *in vivo* does not substantially differ from the *in vitro* findings [31].

Wear is an inevitable consequence of total joint arthroplasty. Metal-on-metal bearings do produce significantly less volumetric wear than metal-on-polyethylene bearings in laboratory experiments and probably *in vivo*. However, as the metal-on-metal bearings produce such small particles, there is some evidence that they generate many hundred times more particles than metal-on-polyethylene bearings [49].

Considering the environmental conditions of the specific tribosystem of the artificial hip joint, all three classical wear mechanisms (abrasion, adhesion and surface fatigue) can apply [40]. Additionally, it has been proved that tribochemical reactions (TCR) play a major role in wear. Typically, metal-on-metal hip joints run in boundary or mixed lubrication mode, depending on the head diameter and clearance tolerances. Hence, TCR layers are expected for metal-on-metal joints and have been described. TCR layers were documented as "deposits" and/or "precipitates", which belies their importance in the tribosystem. Wimmer *et al.* [49] demonstrated that TCR layers do not simply adsorb into the bearing surface; TCR also alter the cobalt-alloy substrate, transforming subsurface layers from solely metallic to composite-like. Since the TCR layer is composed of a nanocrystalline composite of organic, ceramic, and metallic material, direct metal-on-metal contact never occurs in its presence, even without fluid film interposition. Thus, adhesion, which could lead to catastrophic seizure of the contacting surfaces, is prevented. The authors concluded that TCR layers are essential to keeping wear rates low and that more research should be done in order to enhance the formation and stabilization of these layers.

Many hip simulator tests have been conducted to identify parameters influencing the wear behavior of metal-on-metal bearings. Theoretical studies suggest that a larger clearance (the difference in diameter between head and cup) increases wear. A meta-analysis by Kretzer and colleagues [30] concluded that a smaller clearance reduces running-in wear, mainly for implants of 36-mm diameter. However, the minimum clearance is limited because implants may deform slightly during implantation or loading, which can lead to additional contact near the rim of the cup (equatorial contact), resulting in increased friction and wear. Also, for implants with a diameter ≥ 36-mm, an increase in head size reduces running-in wear, but not steady-state wear. If lubrication is insufficient and components are not at least partly separated by a fluid film, wear might increase due to the longer wear path. It was previously believed that the manufacturing method (wrought vs. cast) and the carbon alloy content influenced wear rates [10][23] (**Table 2.**). A review of hip simulator studies disproved the former but could not clarify the latter's influence on wear. Finally, the authors concluded that low surface roughness and low deviation on roundness reduce wear on metal-on-metal bearings [30].

**Table 2.** Characteristics of Some of the Metal-on-Metal Bearings in Use Clinically

| Name and Manufacturer | Product Name | Manufacturing | Carbon Content |
|---|---|---|---|
| Zimmer, Inc | Metasul™ | Wrought | High |
| Biomet Orthopedics Inc | ReCap™ (Hip Resurfacing) | Cast | High |
|  | M2A - Magnum™ | Cast | High |
| Midland Medical Technologies Ltd | Birmingham Hip Resurfacing | Cast | High |
| Wright Medical Technologies | Lineage® | Cast | High |
|  | Conserve®+(hip resurfacing) | Cast | High |
| DePuy Orthopaedics Inc | Ultamet™ CoCr insert for Pinnacle™ Acetabular component | Forged | High |
| Corin Cirencester | Cormet 2000® (hip resurfacing) | Cast | High |
| Encore Orthopedics, Inc | Metal™ Metal | Wrought | Low |

(The processing parameters shown in this table were compiled from various publications and information provided by the manufacturers, and are subject to ongoing modification.)
High Carbon content generally is 0.2% to 0.25%.
Low carbon content generally is less than 0.2%

(Modified from Campbell, P; et al; Biologic and Tribologic Considerations of Alternative Bearing Surfaces; Clin Orthop; Number 418; January 2004) [9]

One of the most attractive and unique feature of metal-on-metal joints is the ability to self-polish *in vivo*. Implant retrieval studies and *in vitro* testing under abrasive conditions have shown that moderate surface scratches caused, for example, by one subluxation event or a transitory third body particle may be considerably polished out during succeeding activity [10].

A cause for concern with metal-on-metal joints has been the systemic metal ion release. Volumetric wear rates and osteolytic potential of metal-on-metal bearings are lower than those of metal-on-PE bearings. However, metallic particles have a greater potential for cytotoxicity, and their number is greater [30]. Despite today's very low wear rates ranging from 0.5 to 2.5 μm/year, increased ion levels in serum compared with other established bearing combinations are observed. Metal ion release, which can form metal/protein complexes and the generation of nanoscopic wear debris, raise concerns regarding particle induced osteolysis, perivascular lymphocytic tissue responses, and metal hypersensitivity [49]. In a study by Tsaousi and colleagues [46], at revision arthroplasty there was a three-fold increase in aneuploidy and a two-fold increase in random chromosomal translocations, which could not be explained by confounding variables. Most interestingly though, metal alloy-specific differences were observed: in the lymphocytes of Ti-alloy prosthesis recipients there was a five-fold increase in aneuploidy, but no increase in chromosomal translocations. By contrast, in lymphocytes from patients with CoCr prostheses there was a 2.5-fold increase in aneuploidy and a 3.5-fold increase in chromosomal translocations. In lymphocytes from stainless-steel prosthesis recipients there was no increase in either aneuploidy or chromosomal translocations. The authors concluded that CoCr particles are genotoxic and cytotoxic to human fibroblasts, and that this toxicity is dose-dependent. Other studies [21][34], have related metal-on-metal bearings with soft tissue changes which have been classified as pseudotumors or aseptic lymphocyte-dominated vasculitis-associated lesion (ALVAL). The incidence of these soft tissue changes appears to be increasing. Revision of these cases is frequently complicated, since the abductors may be stripped from the proximal femur with extensive soft tissue lost; bony necrosis a surrounding much of the proximal femur may also take place. These changes are occurring early on and are often more severe than predictable on x-ray. Revision is difficult and the result of revision for failed metal-on-metal bearings with pseudotumor is poor, with a superior than 50% re-revision rate reported in the short term in one series [16]. Further investigation is needed to ascertain the relevance of these findings and their influence in bearing surface selection.

The first generation of resurfacing hip arthroplasty (RHA), with a metal-on-PE bearing couple that were implanted during 1970s and early 1980s, was associated with poor clinical results. The renewed interest in hip resurfacing follows the introduction of the metal-on-metal articulation. This was, as previously stated, based on the observation that some of the early metal-on-metal prostheses have survived for over 20 years, with low wear and osteolysis rate [34]. Since the introduction of metal-on-metal resurfacing devices, in the 1990s, over 300,000 procedures have been performed worldwide [20]. Multiple studies of short- and mid-term outcomes of resurfacing implants have reported clinical success rates upwards of 94%, with several studies reporting five-year survival rates of 98% [23]. These outcomes are similar to those that have been reported for patients treated with conventional THA. Some investigators have argued that resurfacing may offer advantages over THA, in terms of conservation of femoral bone stock, increased range of motion (ROM), a more normal gait pattern, lower dislocation rates, and ease of revision. In a recent meta-analysis, Marker and colleagues [38], found that, though THA had superior results in the radiographic studies, the clinical assessment suggested a better performance of RHA, with better function and an early return to the previous activity levels. Also, gait studies showed similar or better outcomes for RHA compared to their THA counterparts. One of the concerns with RHA was the potential for a complicated revision procedure with conversion to a THA but the literature shows that, apart from a slightly longer mean operative time, the conversion surgery does not significantly differ from a primary THA. However, RHA patients had a lower Harris Hip Score in the post-operatory period because of higher pain levels. In fact, pain is one of the most commonly reported side effects of the RHA. Fowble and colleagues [19] reported that only 48% of the patients undergoing resurfacing reported complete pain relief, compared with 80% of the patients undergoing THA, though they suggested this might be related to the marked difference in UCLA activity scores (8.2 vs 5.9, respectively). Recently the United Kingdom's Medicines and Healthcare products Regulatory Agency issued a medical device alert requesting that U.K. orthopedic surgeons further investigate the cause of pain in patients with painful metal-on-metal hip arthroplasties and resurfacings, mainly because of the increasing number of reports about revisions of these implants involving soft tissue reactions [47]. Though no other medical agencies, including the FDA, have issued any similar alerts, the higher incidence of painful joints with metal-on-metal bearings remains a matter of concern.

Metal RHA has higher costs than the conventional metal-on-PE bearings. Since it is yet to be proven RHAs superiority over the remaining options, in some countries (e.g. United States) many health plans have developed payment policies limiting the use of metal-on-metal RHA to specific patient populations. Bozic and colleagues' [5] research on this topic led them to conclude that RHA could be both clinically advantageous and cost-effective in appropriately selected men under the age of 65 years and women under the age of 55 years, when considering the initial and subsequent risks, costs, and benefits accrued over a 30-year period. Nevertheless, as recognized by the authors, the study has several limitations, especially the short experience with the RHA that makes any conclusion based on long-term survival of this bearing somewhat speculative.

## VII - Conclusion

In the past, most arthroplasties used metal on polyethylene as a bearing surface and this was related to the appearance of osteolysis and high revision rates. In order to minimize wear debris production, alternative bearings have been used, such as metal on highly cross-linked polyethylene, metal-on-metal, ceramic-on-polyethylene and ceramic-on-ceramic. Each has its own relative advantages and disadvantages and the best option still remains controversial and is continuing in the literature (**Table 3.**). Cross-linking polyethylene has decreased wear rate both *in vitro* and *in vivo* and it remains to be seen if, in the future, osteolysis will be reduced. Ceramic-on-ceramic bearing surfaces show the lowest linear wear, but the material is brittle. Metal-on-metal bearing surfaces show also significant reduction in wear. However, the early accumulation of metallic debris and tissue reaction to them, hypersensitivity reactions, ion toxicity, gene mutations, and carcinogenesis are issues of concern.

**Table 3.** Summary of Relative Advantages and Disadvantages of New Hip Bearing Materials

| Bearing Material | Advantages | Disadvantages |
|---|---|---|
| Polyethylene with elevated cross-linking and high oxidation resistance | Clinical wear is anticipated to be well below the threshold for lysis | Diminished fatigue strength and fracture toughness with increasing cross-linking<br>Smaller wear particles with lower threshold for biologic response<br>Short clinical history |
| Ceramic-on-ceramic | Long clinical track record with overall excellent results<br>Extremely low wear if well functioning/implanted<br>Improved scratch resistance<br>Improved lubrication<br>Good corrosion resistance<br>Biocompatibility and biostability | Infrequent but catastrophic fracture<br>Fracture-related revision complications<br>Inappropriate operative technique (component positioning) may lead to impingement, high wear and/or fracture |
| Metal-on-metal | Long clinical track record with overall excellent results<br>Extremely low wear rates<br>Can self-polish mild surface damage<br>Allows for RHA | Uncertainty regarding adverse long-term biologic effects of metal ions (metallosis)<br>Possibly induces sensitivity in some individuals<br>Pseudotumors<br>Higher costs |

Modified from McKello HA; Bearing Surfaces in Total Hip Replacements: State of the Art and Future Developments. In Sim FH (ed). Instructional Course Lectures. Rosemont IL, American Academy of Orthopaedic Surgeons 165-179, 2001 [39]

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