EUROPEAN ACADEMIC RESEARCH
Vol. VII, Issue 5/ August 2019

ISSN 2286-4822
www.euacademic.org

Impact Factor: 3.4546 (UIF)
DRJI Value: 5.9 (B+)

A retrospective study of the evolution in Total Hip Arthroplasty: Where do the bearings stand now?

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Abstract

Total hip arthroplasty is one of the most performed surgery in the orthopedic department. Since general medicine and especially surgery have constant innovations, Total hip arthroplasty (THA) has not been spared; new techniques, materials, alloys, bearings are being created in order to facilitate surgery, improve lifespan of the joint and minimize the undesirable effects for an overall better outcome. Another compelling reason to find the ideal bearing implant is that younger patients are now targeted since THA indications have expanded; morbid obesity, high incidence of high velocity trauma or strenuous physical activity which slowly damages the joints. Bearings have been through several decades of evolution; each generation proving to be better than the previous one. Ceramics such as Alumnia or Zirconia, Metals such as Cobalt-Chromium and Polyethylene and cross-linked PE have been on the front line treatment in hip replacement with each category having its advantages and shortcomings. Newer metals,

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ceramics and alloys have been produced that are being under trial have shown very promising future. Accurate data from reliable researches have shown that ceramics and high hinge polyethylene are more being used now since metal implants have shown to produce high complication and failure rates with need for early revision. It has also been shown that metal implants have considerable adverse local and systemic effects on the body. Bearing implants in THA is being constantly innovated as new compounds are being in trial to find the suitable alloys for bearings and stand alone implant. This article reviews the most common implants and the latest technological development in the field, together with an objective comparison among them.

Keywords: Total Hip Arthroplasty (THA), Alloys, Metal bearings, Ceramic bearings, Surface processing, Cushion bearing, Innovation

INTRODUCTION

Total hip arthroplasty, THA, also known as the 'operation of the century'[1], is one of the most performed surgery in orthopedics which provides long term durable results. As advancement in the medical field continues, multiple types of bearings have been invented ; with different size, alloys and compositions to increase the overall outcome of both surgery and patient. The ideal bearing is defined with the following characteristics; being inert, with the lowest coefficient of friction, and scratch resistant with low wear[2]. The incidence of THA has drastically increased over the last few decades since newer techniques of approach and bearings were invented. According to Labek et al. [3], in a research in the 2010s, an estimated amount of 2 to 3 millions THAs were done worldwide with a survivorship of about 90% after a 10 year revision. The situation is becoming more challenging as younger and very physically active patients; <50 years old undergo THA, meaning that the current technologies in bearing implants do not suffice for the patient or the national health care system [4] , thus the need of new bulk materials and bearing coatings.

Metal on Metal Hip Resurfacing (MoM HR)

First attempts to resurface started in the 1930s and 1950s. Resurfacing of the damaged hip joint seemed to be the best arthroplasty choice considering the stability and minimal loss of bone during surgery. Although the procedure yielded good short-term results, a high rate of failure was noted due to the high wear rate leading to severe osteolysis. MoM HR lost popularity when metal on polyethylene bearing surfaces were successfully implanted in the early 1960s and 1970s and when resurfacing attempts notably failed by Wagner of Germany and Tharies of USA[1] [5].

Metal on Metal Bearings (MoM)

MoM bearings were an interesting alternative and rapidly gained popularity in the 2000s due to their theoretical properties in implants; generating less wear particles, ability to use larger femoral head thus improving hip stability and range of movement. The most common material used in Metal-on-metal bearings is cobalt-chromium (CoCr)[6]. CoCr bearings were widely used in the 2000s but were found to have mechanical problems such as taper corrosion and releasing metal ions which have local and systemic adverse effect on the human body[7].

Complications of MoM bearings

Although MoM bearing looked appropriate for implants, its use declined drastically during the last 15 years due to evidence of their high failure rates and long term side effects [8].

A revision of 1062 THA were done over a 5 year period revealed that MoM bearing failure was up to 15.8%, being one of the major causes of implant failure[9]. Thus hip implants with metal cross-linked polyethylene and ceramic liners are were chosen to become the modern implants of choice. From several recent studies, it have been proven that metal ion wear debris from the MoM hip implants were even more damaging than the debris generated from conventional polyethylene[10] [11] [12] [13] [14]. On the other hand, retrospective studies have shown that cobalt and chromium metal ions from the bearing interface liners exert toxic local and systemic effects on the human body [10]. Inflammatory cells uptake the metal ions and create a cascade which leads to local tissue reactions; they include formation of pseudotumors, soft tissue necrosis along with bone osteolysis[11][12]. These reactions are believed to be the major cause of early implant failure, thus the need for early revision. Metal ions are also systemically uptaken by blood, plasma, serum,urine, cerebral spinal fluid leading to moderate to severe adverse systemic effects on the body which include brain damage, peripheral neuropathy, vision and hearing impairment, cardiac problems and thyroid toxicity[11][15].

Ceramic bearing

Since the introduction of ceramic bearings, there has been a high success rate in its clinical use[16]. With constant evolution of the alloys, more resistant ceramics have been created for implantation. Ceramics are biologically inert, have a very low coefficient of friction, are well and easily lubricated and have acceptable wettability properties making them a suitable orthopaedic bearing surface[17] Alumina (Al_2O_3) and zirconia (ZrO_2), zirconia-toughened alumina (ZTA), alumina-toughened zirconia (ATZ) and Silicon nitride, (Si_3N_4), a non-oxide ceramic, have given a boost to newer bearings. Al_2O_3 remains one of the most common ceramic bearing used in orthopedic surgery, and oxidized zirconium has taken over ZrO_2 as bearing surface. Composites made of Al_2O_3 and ZrO_2 have been designed to provide more resistant orthopedic bearings with stronger tensile strength and better wear properties[18] [19].

Despite alumina and other ceramics were chosen as bearing materials due to their lower wear properties, scratch resistance and overall strength, they were found to be brittle and were easily prone to fracture[20]. To accommodate this, newer generation (currently the fourth generation) of composite ceramic bearings such as Biolox Delta (Ceramtec, Plochigen, Germany) have merged zirconia with chromium oxide, yttrium and strontium to prevent crack formation and propagation[21].

Advantages

Main advantages of ceramic femoral heads over metal femoral heads bearing with crosslinked polyethylene (CoXLPE vs MoXLPE) are as follows: Metal ions are released from metal femoral heads due to wear other time thus causing oxidation and harm to surrounding tissues and in addition, causing surface roughening whereas ceramics are chemically inert with no such issues . The polished surface of ceramics have much lesser coefficient of friction as compared to metal; therefore it has a much lesser wear over time; joint lubrication is much better achieved with ceramics; Ceramic heads have lower susceptibility to surface scratching[22][23].

Shortcomings

Ceramic on Ceramic bearings, despite excellent clinical trials, have not been widely used due to the following: brittleness causing fractures, squeaking, dislocation and cost. These have decreased since the introduction of newer ceramics, namely alumina, but it nonetheless still remains[24]. Fractures in CoC are very rare and are normally associated with high velocity traumas such as motor vehicle accidents or fall from heights. The usual method of reparation is to replace the components which were affected[25].

Comparing MoM vs MoP, CoP and CoC

From a retrospective study made by L.T Kleeman et al. [8] , MoM bearings were compared post operatively to MoP, CoP and CoC bearings respectively and yielded concise results. 288,118 patients were compared between 2005 and 2011 (all of them underwent primary unilateral total hip arthroplasty); 57% received MoP bearing implant, 28% MoM bearing implant, 12% CoP bearing implant and finally 3% obtained CoC bearing implant [8]. It was found that MoM bearings yielded a much higher percentage of wound complications, periprosthetic infection, osteolysis and mechanical complaints with the need of early implant revision. Several reviews also supported the findings, notably Bozic et al.[26] and Voleti et al.[27] where the complication incidences were 3.37 higher in MoM than in MoP implant bearings; with complications such as aseptic loosening, dislocation and fracture occured commonly.

Innovation

Bulk materials

The logical option to have a better implant is to improve the whole implant itself; by replacing the bulk material of the implant with a superior one which would have the properties closer to the ideal bearing implant and less or minimal complications or failure[28].

Carbon-fiber reinforced polyetherertherketone (CFR-PEEK)

CFR-PEEK can be manufactured into a large range since its chemical and physical properties can be altered easily through moulding process[29]. A study of 30 THA patients was done in 2001 who had a 30% pitch fiber content in the implants. Only 1 revision was done due to infection following trauma. It was also reported that low fiber fragments levels were observed in the surrounding tissue[30]. Clinical trials are still underway and results are not yet available up to date.

Coatings

Coatings have been of major interest lately because they are available to increase the lifespan and minimize failure of the implant as they change the surface properties of the bulk material. The main issue with coating is the adherence of the latter to the bulk surface[31].

Ceramics coatings

Since the properties of ceramics are favorable for a suitable bearing surface in THA, extensive research have been done in the field to improve/find better materials for bearing implants. The main concern about ceramic implants are their brittleness and predisposition to fracture [17][18][19].

Sapphire

Sapphire is currently being researched as a potential bearing surface since it has all the requirements of implants; naturally inert and biologically compatible, low coefficient of friction and high wear resistance. A trial of 5 patients whom received sapphire femoral heads during their THAs have yielded positive results during a 1 to 5 year follow-up[32] [33]. Of course, this does not conclude anything as further studies are needed but shows another promising area to exlpore.

Metals coatings and bulk materials

There have been main concerns on MoP and MoM bearing implants due to their high complication and failure rates. Innovation is being made in the design and alloys to reduce release of metal ions and wear as well as coefficient of friction[34].

Silicon nitride

Silicon nitride (Si_3N_4), unlike metals, is translucent to X-rays and being non-magnetic, it is ideal for MRI/CT SCANs of soft tissues and bones near to the Si_3N_4 implants. Si_3N_4 is bio-compatible and porous and has been shown, via in vivo studies, to support bone in-growth and in bone fusion in spinal surgeries .Si_3N_4, nowadays, is being extently used to develop bearings as coating or stand alone component that can improve the wear and longevity of prosthetic hip and knee joints[18].

Titatium nitride

TiN (Titanium nitride), another non metal, is scratch resistant, biologically inert with low coefficient of friction. Its use is mainly in the coating of femoral heads where it suitably increases wear resistance, decreases release of metal ions and improves osseointegratrion[28]. The introduction of TiN on femoral heads coating was done in the 1990s but clinical data is insufficient to draw any decisive conclusion. A study revealed a 95% survivorship at 11 years and loosening rates ranging from 25 to about 44%[34].

Diamond-like-carbon

Diamond-like carbon coatings (DLC) are known in the metal industry to improve corrosion resistance and lifetime of metals ,e.g stainless steel. They are being considered in the field of orthopedics as bearings as their material properties fit the desired standard of bearing coatings; very hard, scratch resistant, low wear, and minimize release of metal ions in the bloodstream [31]. But the first trials have not been too promising, there was implant failure, inferior survivorship compared to aluminium oxide at <10 years and coating delamination[35].

Alumina

Alumina coating consists of aluminium oxide on the outside layer which serves as surface, deeper layers are made of alumina and an inner layer of aluminium-titanium alloy. Primary studies revealed that the ceramicized surface was 2.5 times harder than the alloy, lower coefficient of friction and more than 250 times improved wear compared to an aluminium ball[31][36].

Nanocrystalline diamond

Nanocrystalline diamond (NCD) coating has shown promising results in biocompatibility in vitro settings [37]. NCD was used as a coating surface on silicon nitride and underwent laboratory tests; it was shown that after roughly a 5 year equivalent use of the implant in THA, there was no cracking, no squeaking and superior wear resistance, better than the 4th generation of ceramics[23].

Compliant/Cushion Bearings

This innovative approach describes the mechanism whereby a hard alloy head goes into a soft counterpart to mimic as much as possible the natural function of the cartilage. It is widely known that fluid, namely the synovial fluid, flows between the joints. Therefore, the aim of this bearing is to allow fluid between the bearing joints and imitate the natural cartilage [31]. Polyurethane (PU) has been considered as a potential bearing material in the early 1960s. But interest waned after the emergence of polyethylene (PE) few years after. New studies recently put PU again in the spotlight[31]. Since it can be shaped into many forms, polycarbonate urethane (PCU) has been shown,via in vitro studies, that it is more resistant than PE[38]. The main use of PCU in THA is to work as the lubricant in the joint. After several hip simulations, it was demonstrated that PCU with a CoCr head had less wear compared to a PE implant, lower damage level and better ageing resistance [39].

Hydrogels are networks of polymer chains that has a 99% water absorption capacity and possess elasticity as well as viscosity comparable to human tissues. They form a thin layer of hydrated film under normal conditions which is essential to counter friction and torque[40]. The main issues with hydrogels are that they are not mechanically stable and are difficult to attach to a substrate. Therefore new processing techniques and composite materials such as PVP or PVA are used to counter the problem. So far, after simulations, it has been observed that bearings coated with hydrogels have had a very high wear properties [41][42].

Horseshoe/Cambridge cup

The horseshoe cup consists of an inner UHMWPE bearing surface and outer CFR-PBT (carbon fiber reinforced polubutyleneterephthalate) shell with 6 spikes on the back of the bearing of and ressembles a horseshoe [43]. Several studies have shown that after following 11 patients with horseshoe cups, there was an overall decrease in bone density. Histological analysis also revealed mononuclear inflammatory response against polymer particles and carbon fibers but without osteolysis [44]. The second generation cup, the MITCH-PCR cup, saw a change in the spike positioning and distribution and CFR-PBT was replaced by CFR-PEEK [45]. A randomized controlled trial performed by Field et al.[46] in 25 MITCH-PCR cups with alumina heads on stainless steel or titanium stems revealed a 96% survivorship during the first 3 years, 5 experienced loosening with the titanium stem, lower decrease in bone mineral density as compared with CFR-PBT. Further studies are needed to have an accurate data/report on the overall performance of the bearing.

Surface modifications

Surface modification implies the surface processing of the bulk material which, in contrast to surface coating, does not change the bulk material [31]. This is done mostly by the thermal diffusion of gas, often oxygen, from the top surface in to the inner surface. The main goal of this approach is to increase the strength and resistance of the surface to decrease third body wear [29].

Surface oxidized zirconium

oxidized zirconium (OxZr) surface is obtained by the ceremification of zirconium alloy surface with thermal diffusion of oxygen on the surface [31]. Simulations have demonstrated that OxZr bearing surfaces have drastically decreased wear problems against PE by >40% [47]. It also has a higher wettability and hardness which would be ideal for the formation of film-lubricated layers between the joint and adhesion superior to TiN coatings [48][49]. Recent studies have shown that there was increase in wear against PE after closed reduction of the femoral head and delamination [50]. OxZr is seldomly used nowadays, young and active patients are more targeted by this bearing implant [31].

Oxidized titanium

Titanium oxide(TiO_2) is naturally formed at the surface of titanium alloys. It is similarly compared to TiN in their ceramic like nature. The protective layer offered by TiO_2 on the bulk material is too thin to withstand heavy duty, therefore, forced oxidization is done on the material [51] which increases the layer of oxide on the surface resulting in a much improved strength and corrosion resistance even after severe surface damage [52]. In vitro studies revealed that TO-Ti had a better wear resistance compared to TiN or DLC [53][54]. Therefore the use of titanium oxide in bearing surface looks promising for the future.

CONCLUSION

Total Hip Arthroplasty has come a long way since it was first time performed. Several techniques and bearings were invented during the decades with the sole purpose of increasing the lifespan of the bearing implant. This has been done by finding alloys or new bulk materials which have strong scratch resistance, high wear resistance and very low coefficient of friction. The challenge is still ahead since no ideal bearing implant has yet been discovered and since the indications of THA has expanded involving much younger and active patients nowadays than it did decades ago. It is important that more bearing alloys or bulk metals are researched so that the suitable implant may be used on a need-specific patient such as specific allergy to a material, weight of implant, cost of implant, profession of the patient and so on. This review provided an update on the current bearings used in THA since its very beginning along with new bearings currently under laboratory and/or clinical trials. From conventional metal on metal bearings to ceramics, surface processing and cushion bearings, with developing technologies, the ideal implant does not seem theoretical anymore.

Acknowledgement
Nil
Conflict of Interest
The authors declare no conflict of interest
Funding/Grant
Nil

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