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Advancements in ceramic-on-ceramic bearing materials for total hip arthroplasty: Properties, challenges, and future directions

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Abstract. Total hip arthroplasty (THA) is a vital procedure for addressing hip injuries and end-stage arthritis, offering relief to millions annually. However, long-term issues like femoral headwear and osteolysis persist, with 25-year survival rates of around 77.6%. Material selection significantly influences THA outcomes. This article investigated five typical ceramic-on-ceramic (CoC) bearing materials, including alumina, zirconia, zirconia-toughened alumina (ZTA), delta ceramic, and sapphire. Alumina, known for hardness and wear resistance, improved with lower fracture rates, and some squeaking and zirconia ceramics addressed fractures but require impurity reduction. ZTA combines alumina and zirconia, excelling in mechanical properties but also exhibiting squeaking. Optimized with nanostructures, delta ceramic shows fracture resistance despite occasional squeaking. Sapphire offers excellent biocompatibility but requires complex manufacturing and more clinical trials. The quest for optimal THA-bearing surfaces is ongoing, demanding rigorous research and collaboration.

Keywords: Total Hip Arthroplasty, Ceramic-on-Ceramic Bearings, Bearing Materials, Alumina, Zirconia.

1. Introduction

At present, hip injury is a serious but common medical problem. More than one million people need surgery to solve serious hip problems each year [1]. For severe hip injury, total hip arthroplasty (THA) has achieved some surprising results after decades of development. This treatment provides pain relief and functional improvement for patients with end-stage arthritis and is considered one of the most successful surgeries in medicine [2]. More than 300,000 total hip replacement surgeries are performed in the United States each year [3].

However, in the long-term use of artificial hip joints, there are still problems. The wear of bottom profile dimples on the femoral Head in total hip arthroplasty as well as osteolysis, can cause series issues [4-6]. However one study showed that the survival rate of an artificial hip after 25 years was only 77.6%. On the other hand, avoiding osteolysis and aseptic loosening is vital for patients to recover eventually.

The choice of hip material and the measures implemented in THA surgery have a great influence on the postoperative effect. The clinical application of polyethylene in THA significantly reduced the incidence of postoperative adverse reactions [7], and proper physic therapeutics before and after surgery can also speed up the patient's recovery [8].

At present, the mainstream bearing material choices are diverse. They were mainly metal-on-metal (MoM), metal-on-polyethylene (MoP), ceramic-on-ceramic (CoC), or ceramic-on-polyethylene (CoP) materials [9]. MoP is the most-used choice, but usually for the elderly. MoM has lower osteolysis and wear rates but performs destruction of the periprosthetic soft tissues in long-time use. CoP obtained high patient satisfaction at 5 years but also reported similar osteolysis. In the latest decade, CoC has gained wider use for its low coefficient of friction, low risk of wear, bone lysis and loosening, smaller wear surface and osteolysis volume and minimal release of wear particles [1]. With the continuous development of ceramic materials, the material selection in CoC has been very diverse, such as Alumina, Zirconia, Zirconia-toughened alumina, Delta ceramic 82% alumina and 17% zirconia and Sapphire. In view of the excellent properties exhibited by CoC, this review will summarize the properties, composition, advantages and disadvantages of CoC as well as the selection and optimization in different situations and give some possible optimization methods.

2. Ceramic-on-Ceramic Materials

2.1. Alumina

Alumina ceramic material is one of the first ceramic to ceramic bearing materials used in THA for its high hardness (>2000HV) and high wear resistance [10]. Alpha-phase alumina has a corundum structure, which ensures its stability and produces inert wear debris, avoiding the possible cancer risk caused by dissolution. However, there are still many fracture cases in the early days. Boutin believes it is mainly due to the lack of appropriate standards for early alumina ceramic materials [9]. Osteolysis used to be common in total hip replacement. Yoon believes that the phenomenon is mainly caused by larger particles of ceramic fragments, but with the development of third-generation ceramic technology, the particle size inside has been greatly reduced, the new alumina ceramic material has been able to achieve low fracture rate, low aseptic loosening rate and low osteolysis rate [11]. But during follow-up, there was also a squeaking phenomenon. However, this phenomenon is believed to be caused by severe flexion and internal rotation, which has little impact on the patient's life and does not require revision [12].

2.2. Zirconia

To address ongoing worries regarding fractures in vivo during total hip arthroplasty in the 1980s, zirconia ceramics were introduced in 1985. These ceramics included partially stabilized zirconia employing magnesia (Mg-PSZ) and a composition known as Tetragonal Zirconia Polycrystals (Y-TZP), which was doped with yttria By utilizing a phenomenon called phase transformation toughening, improved mechanical properties are achieved in doped zirconia [13]. It is also proved that Mg-PSZ has good biocompatibility. But, Mg-PSZ exhibits a certain level of porosity, which can have a detrimental effect on the wear rate of UHMWPE sockets when coupled with zirconia ball heads [14]. Furthermore, various technological considerations may have been considered. Challenges arise in the production of Mg-PSZ precursors that are completely free from impurities such as SiO2, Al2O3, and other contaminants [14]. Impurities will increase, reducing the mechanical properties of the material and its stability in a wet environment. Consequently, these challenges might have influenced ball head manufacturers to redirect their focus towards TZP materials. Between 1985 and the turn of the century, more than 600,000 femoral heads made of Y-TZP were successfully implanted. However, a notable shift in manufacturing techniques occurred in 1998, and led to a significant rise in fractures starting from 2000, with many fractures occurring within months after the implantation procedure [13].

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2.3. Zirconia-toughened Alumina (ZTA)

Zirconia-toughened alumina (ZTA), often referred to as Biolox® delta, represents a composite material consisting of 75% alumina and 25% zirconia, where alumina serves as the predominant constituent. Over the past decade, this unique material has attracted significant attention thanks to its exceptional mechanical properties, outstanding resistance to wear, and impressive biocompatibility [15]. These attributes make it a particularly ideal choice for applications involving total hip arthroplasty (THA) bearings' surfaces and addressing concerns surrounding zirconia-rich materials [16]. The fundamental principle driving ZTA's excellence revolves around enhancing fracture toughness and strength compared to pure alumina while preserving crucial alumina traits like hardness, stiffness, and thermal conductivity [17]. This achievement can be realized through two different methods: phase transformation and short fibers. The utilization of zirconia's intrinsic tetragonal-to-monoclinic phase transformation is integrated into ZTA as a reinforcing element. Another method is to incorporate short fibers into the ceramic matrix so that the material's toughness is significantly reinforced [16]. Impressively, ZTA showcases exceptional mechanical prowess, boasting a bending strength of 900MPa, compression strength of 2900MPa, Young's modulus measuring 285MPa, a fracture toughness rating of $6.9 MPa\sqrt{m}$, and a microhardness value of 1500HV [17]. Nonetheless, ZTA shares the same weakness with alumina: squeaking. A comprehensive study conducted by Lim et al. has meticulously documented instances of squeaking, with prevalence ranging from 0.3% to 20% among patients who received total hip arthroplasty utilizing hip implants equipped with Biolox® delta ceramic-on-ceramic (CoC) bearings [18].

3. Delta ceramic

Delta ceramics is a proven medical material that has been commercially produced since 2000 [19]. It is mainly composed of alumina but optimized with nano, strontium oxide and yttria-stabilized tetragonal zirconia. This optimization greatly reduces the possibility of potential cracks inside the hip and significantly improves mechanical strength [20]. Ceramic materials are widely used in THA surgery for their high hardness and wear resistance, but these characters also cause fracture risk under violent impact [19]. Docter Lee reviewed 118 revision THAs using delta ceramic and found the survival rate to be 91.6% in 12 years. No ceramic fractures or ceramic chip fractures under X-ray were reported, which used to be common in THA [21]. This demonstrates the excellent properties of this material in terms of fracture resistance.

However, a study group from Finland pointed out that this material has a squeaking problem. In their research, they reviewed 301 patients (336 hips) and found 52 patients (54 hips, 17%) to have squeaking problem and 48% rated the sound as frequent. They thought this ratio to be surprisingly high in patients and does not vary with the brand of materials [22]. Cases of squeaking also occurred in other studies, but the proportion was not as high, generally less than 10%. This noise is not noticeable and does not have a significant impact on patients' quality of life, and the definition of what is a squeak is less clear. Many noises caused by other causes are also considered to be squeaks. The consequences of this squeaking are still unknown, and it has been suggested that it may increase the load around the implant and cause wear that may affect the survival rate of the implant [23]. Therefore, more research and clinical trials are needed for this phenomenon.

4. Sapphire

Sapphire is the purest form of alumina with no porosity or grain boundaries. Sapphire friction pairs need to be specially purified high-purity alumina crystallized under vacuum conditions of 2100 degrees Celsius [24]. An article from Ukrainian Academy of Medical Sciences, Kharkov points that the failure cases in THA are mainly caused by nanoparticles that are worn off in the hip joint, which are non-inert particles that can deposit in other parts of the body and cause more severe disease. The sapphire hip joint they developed showed a very low coefficient of friction, extraordinary biological inertia and the best biocompatibility possible in current materials, ensuring the artificial hip can be used long after surgery. However, due to the special processing technology required to manufacture sapphire hip joints, higher technical requirements are put forward for the producers of this material. The material's surface must reach a sufficiently high level of smoothness to ensure an extremely low coefficient of friction and long-term use in the human body. Additionally, its long production cycle means it cannot be widely used in patients who need THA surgery urgently [25,26]. Due to the lack of clinical trials on this material, the small sample size, and the limited literature number, its final effect still needs further large-scale trials.

5. Conclusion

The domain of total hip arthroplasty (THA) has witnessed significant advancements in addressing the intricate issues associated with hip injuries and end-stage arthritis, thus presenting a promising remedy for patients necessitating hip joint replacement. The materials employed for THA-bearing surfaces has undergone rigorous development and improvement, each characterized by its distinct merits and constraints. Diverse materials, including metal-on-metal (MoM), metal-on-polyethylene (MoP), ceramic-on-polyethylene (CoP), and ceramic-on-ceramic (CoC), have all assumed pivotal roles in the realm of THA. Among these, CoC bearings, with their distinctive attributes, have notably garnered consideration and adoption.

Alumina is one of the earliest ceramic substances used in THA, boasting commendable hardness and wear resistance. While considerable progress has been achieved in mitigating early issues pertaining to fracture rates through technological innovations, residual concerns, such as the occurrence of squeaking, warrant further comprehensive investigation. Conversely, the introduction of zirconia ceramics in the 1980s aimed to counteract fractures and has demonstrated superior mechanical properties. Nevertheless, challenges related to impurities and fractures in specific zirconia ceramics have prompted continuous research and refinement. Transitioning to zirconia-toughened alumina (ZTA) frequently denoted as Biolox® delta, the composite material amalgamating the strengths of alumina and zirconia presents remarkable mechanical properties and wear resistance. Notably, ZTA shares the squeaking phenomenon observed in pure alumina. Another promising CoC material, delta ceramic, subject to optimization with nanostructures, has exhibited commendable potential in fracture resistance. Although instances of squeaking have been reported in a subset of patients, the collective performance metrics suggest its candidacy as a valuable addition to the THA material repertoire. Sapphire, characterized by its exceptional purity and biocompatibility, manifests significant promise within the realm of THA. Nonetheless, due to the exacting manufacturing prerequisites and the paucity of comprehensive clinical data, rigorous research and extensive clinical trials remain imperative to ascertain its long-term efficacy.

In summation, the judicious selection of bearing materials for THA is a pivotal decision influenced by multifarious factors, encompassing patient demographics, material attributes, and clinical ramifications. While CoC materials, encompassing alumina, zirconia, ZTA, delta ceramic, and sapphire, proffer tantalizing prospects for the augmentation of THA, the associated unique challenges necessitate continued exploration.

5.1. Discussion

The deliberation surrounding the choice of bearing materials in total hip arthroplasty (THA) is a multidimensional process shaped by an array of factors encompassing patient demographics, material attributes, and clinical ramifications.

Patients' needs play a crucial role, especially for implants used in treating younger and more physically active individuals which require the longevity of the implants. Within this context, ceramic-on-ceramic (CoC) materials, notably delta ceramic and zirconia-toughened alumina (ZTA), emerge as promising candidates, primarily due to their impressive mechanical properties. However, the caveat of potential squeaking, particularly concerning delta ceramic, mandates meticulous patient consultations and informed decision-making. Each type of CoC material has its own challenges; alumina, renowned for its hardness and wear resistance, has witnessed considerable advancements in mitigating fracture rates but continues to confront the issue of squeaking. Zirconia ceramics need ongoing efforts to remove impurities and reduce the risk of fractures, whereas ZTA inherits the squeaking phenomenon from its pure alumina counterpart.

Prospective research initiatives and clinical trials are crucial as the ever-evolving domain of THA explores pioneering manufacturing methodologies and material refinements to address established hurdles. Striking a balance between technological advancements and their real impact on patient care is essential, as seen with the cautiously optimistic approach to sapphire. Large-scale clinical trials are necessary to authenticate the long-term efficacy of nascent materials such as sapphire. Ultimately, the goal of these material innovations is the augmentation of patient outcomes and the enhancement of the quality of life for recipients of THA. This persistent pursuit of the optimal bearing surfaces in THA is an exciting journey with the potential to transform the field, requiring collaborative endeavors to ensure that these materials culminate in discernible patient advantages.

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