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Ceramic-on-ceramic total hip arthroplasty: A new standard—Affirms

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ABSTRACT

Highly cross-linked polyethylene has emerged as an improvement over conventional polyethylene in terms of wear characteristics and osteolysis in total hip replacement; however, decreased material properties could make it unsuitable for use in high-demand patients. Modern ceramic-on-ceramic bearings display extremely low wear and durability that make them an ideal bearing surface. Unfortunately, certain implant designs have been associated with squeaking, which has discouraged widespread use. Proper implant selection, orientation, and surgical technique can lead to optimal results with ceramic bearings, and substantial mid- to long-term data exists to support their use over other bearing surfaces in total hip replacement.

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1. Introduction

Metal-on-polyethylene has been established as a reliable bearing couple in total hip arthroplasty (THA). However, questionable resistance to wear, long-term durability, and biologic effects of polyethylene wear debris on component fixation have raised concerns about its use in younger, more active patients. Alternative bearing surfaces have frequently been utilized in an effort to improve THA longevity in this patient population. These alternatives generally include metal-on-highly cross-linked polyethylene (HXLPE), ceramic-on-HXLPE, metal-on-metal, and ceramic-on-ceramic (CoC) bearings. Although metal on HXLPE has been the most commonly used bearing couple in recent years, the clinical experience with this bearing is comparatively short, with long-term data still pending. In contrast, ceramic-on-ceramic bearings have been in clinical use for 4 decades and have experienced continual improvement during this period. Owing to the unique material properties of CoC bearings, we believe this bearing couple will ultimately prove superior to ceramic-on-HXLPE and metal-on-HXLPE bearings for younger, more active patients.

2. Highly cross-linked polyethylene

HXLPEs were developed in an effort to reduce the wear and associated osteolysis seen with ultrahigh-molecular-weight polyethylene. The adoption of HXLPE came after multiple in vitro wear simulator tests that showed that radiation cross-linking dramatically reduced wear rates [1,2]. Wear particles from conventional polyethylene have been

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well-documented to incite immune system-mediated osteolysis, resulting in aseptic loosening of THA components and loss of acetabular and femoral bone stock.

Mid-term data and minimal long-term data (>10 years) are now available for the first-generation cross-linked polyethylenes. Babovic and Trousdale [3] in 2013 reported minimum 10-year clinical and radiographic outcomes of HXLPE in patients aged under 50 years. There was no radiographic evidence of osteolysis or component loosening, and mean femoral head penetration was 0.020 ± 0.0047 mm/year. However, 70/124 hips were excluded due to incomplete follow-up. Kurtz et al. [4] performed a systematic review of studies of first-generation HXLPE compared with conventional polyethylene liners, finding that mean 2-dimensional linear penetration rates of HXLPE liners was 0.042 mm/year based on 28 studies compared with 0.137 mm/year for conventional polyethylene liners based on 18 studies. Mean linear penetration rate of metal on HXLPE (0.038 mm/year) was reported to be less than ceramic on HXLPE (0.058 mm/year), and the incidence of osteolysis was 87% lower in patients with HXLPE liners compared with patients with conventional polyethylene liners. Notably, osteolysis still occurred. The effect of head size was also reported, with weighted averages of penetration rates of larger cobalt–chromium head sizes into HXLPE to be lower (0.027 mm/year) than smaller head sizes (0.027 mm/year). The authors point out that few studies report data for 32 mm or greater femoral head sizes against HXLPE, and more studies need to be completed on these currently more common head sizes. Furthermore, for all the end points, the authors highlight the heterogeneity of implants as well as methodologic variation in measuring radiographic penetration across the pooled studies. Bragdon et al. [5] published a multicenter study on remelted HXLPE. No cases of periprosthetic osteolysis were reported. Femoral head penetration rates did not correlate with time across standard-sized heads (28–32 mm); however, large head (36 mm) wear rates were 27 μm/year versus 4 μm/year with the standard head sizes. The study did not address survivorship of implants. The data on performance of second-generation HXLPEs, which include mechanical and sequentially annealed polyethylene as well as vitamin-E-doped polyethylenes, is only now emerging due to their relatively recent introduction.

Despite these improvements in polyethylene wear and in vivo performance, there are continued concerns with HXLPE, which could become more evident as it moves into its second decade of service. The induction of cross-linking with radiation is well known to proportionally decrease polyethylene mechanical properties [6,7]. Furthermore, post-irradiation processing to diminish free radicals in order to prevent oxidation contributes to loss of mechanical properties; annealed polyethylenes contain residual free radicals and have been observed to undergo in vivo oxidation at the rim [8,9]. MacDonald et al. [8] retrieved 307 HXLPE liners, of which 80 were annealed and 160 were remelted. Oxidation was evaluated using Fourier transmission infrared spectroscopy (FTIR), and annealed liners had higher oxidation indices at both the backside surface and the rim compared with remelted liners. Over half of the retrieved annealed liners exhibited severe oxidation, which exceeded the American Society for Testing and Materials (ASTM) oxidation index for severe loss of mechanical properties. Furmanski et al. [10] reported optical and SEM-identified cracks in six of nine retrieved annealed HXLPE liners implanted for 3 days to 4.11 years. Remelting removes free radicals more completely than annealing; however, it reduces the crystallinity of the HXLPE and renders it less fatigue resistant and reduces material toughness [11,12]. Numerous case studies have documented fractures at the liner rim of remelted polyethylenes, requiring revision surgery [13]. Tower et al. [14] retrieved four annealed Longevity liners and noted no measurable oxidation, though they observed cracking or rim failure of the liner along the groove that engages the locking ring of the shell. They concluded that thin polyethylene at the cup rim, vertical cup alignment, and susceptibility of HXLPE to fatigue damage relative to conventional polyethylene were important factors contributing to failure. Schroder et al. compared 39 randomly chosen Longevity HXLPE liners to 36 randomly chosen Trilogy conventional polyethylene liners and noted equivalent damage scores by two independent graders [15]. However, rim cracking was present in five (13%) of cross-linked liners and one (3%) of conventional liners, raising concern regarding the long-term fatigue performance of cross-linked liners. Cup malpositioning, thin liners, and liners with an elevated rim have been associated with rim cracking. A recent study by Ast et al. [13] analyzed voluntary reports to the United States Food and Drug Administration (FDA) of fractures in remelted Longevity liners, and 74 cases were identified. They observed an apparent increased risk of fracture with liners less than 4.8-mm thick at the rim and less than 7-mm thick at the weight-bearing surface. In summary, while wear performance and osteolysis have been reduced, first-generation HXLPEs appear to be particularly susceptible to fatigue and oxidation-related damage. More studies are particularly needed in the young and active patient population.

3. Evolution of ceramic-on-ceramic bearings

Ceramic bearing surfaces were initially used in France in 1970 by Pierre Boutin and subsequently by Mittlemeier and Walter in Germany in 1974. In his own research, Boutin [16] determined that alumina was a uniquely biocompatible material, and he even designed one of the first cyclic wear-testing experiments to demonstrate the low wear of the bearing. Additional aims were to reduce the detrimental biologic effects of polyethylene wear debris as well as to provide a more wear-resistant bearing for more active patients [17]. Due to their ionic structure and hydrophilic surface, ceramics are highly wettable and tend to attract fluids across the entire surface rather than beading, as happens with cobalt–chrome [18]. When coupled in a fluid-filled environment, ceramics display fluid–film and hydrodynamic lubrication modes. Ceramics are already in their highest state of oxidation and are thus resistant to corrosion, or additional degradation [16,18].

An initial limitation to widespread use of the CoC bearing was ceramic fracture due to the brittle nature of the early-generation ceramics [19,21]. After the initial experience with

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