Review article

New alternate bearing surfaces in total hip arthroplasty: A review of the current literature

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ABSTRACT

As indications for total hip arthroplasty (THA) have expanded, the incidence of THA has increased among younger patients, who live longer and tend to place more strain on implants via higher activity levels. This demographical shift accentuates the importance of advancing innovation to ensure implant longevity for younger and more active patients. Future innovation, as it pertains to THA components, is likely to focus on modifying implant designs and tribology in conjunction with identification and application of newer biomaterials. By reviewing the literature for development status of various materials and novel design advancements in THA component outside of the standard highly cross-linked polyethylene, this investigation provided an update on the current and future status of design initiatives as they pertain to THA. Though the highlighted alternative bearing surfaces have shown promising *in vitro* and limited, yet encouraging clinical data, they lack larger and longer-term clinical trial results. Further research and innovation is warranted to identify the optimal bearing surface to most effectively accommodate for the trend of younger and more active patients undergoing THA. Implant longevity is crucial if the clinical success of THA is to be maintained.

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1. Introduction

As the indications for total hip arthroplasty (THA) have expanded, the incidence of THAs being performed in younger patients has increased, with patients younger than 65 years expected to account for more than 52% of primary THAs in 2030.¹ Moreover, younger patients who undergo THA tend to place more strain on their implants via higher activity levels and also live longer, which may place them at higher risk for a revision procedure.^{2,3} This shift in demographics accentuates the importance of continued innovation to ensure implant longevity for younger and more active patients.⁴

Ideal THA components should mimic normal physiology with respect to tribology.^{5,6} In addition, the bearing couples should have a low coefficient of friction, high surface hardness with low ductility and scratch resistance, and generate a low volume of wear particles (Fig. 1).⁵ Moreover, surfaces exposed to tissues should be

non-cytotoxic, biocompatible, and bioinert.^{5,6} There is evidence suggesting that it may be beneficial for the elastic modulus of the components to be similar to bone.^{7–12} The likely direction of future innovation as it pertains to THA components will be focused on modifying implant designs in conjunction with the use of newer biomaterials.^{5,6}

Given the predominance of highly cross-linked polyethylene (HXLPE) as the standard for bearing surfaces,^{5,13} the purpose of this review was to provide an update on the development status of various materials and design advancements in THA components. Specifically, we evaluated: 1) the properties of new materials being developed for use in THA; and 2) any studies with limited clinical data to support larger, clinical trials of these materials.

2. Materials and methods

A search of the PubMed, Embase, and Scopus databases was undertaken in July 2017. The following search terms were used in individual searches: “alternative bearing surfaces,” “total hip in young patients,” “highly cross-linked PE,” “vitamin E cross-linked PE,” “oxinium,” “oxidized zirconia,” “yttria, zirconia, hip,” “silicon nitride, hip,” “silicon nitride, joint,” “horseshoe cup,” “Cambridge

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Fig. 1. Comparison of volumetric wear rates (mm³ per year or per million cycles) among THA bearing surfaces.^{27,43,46,62,63}

*The materials are labeled as the alternate bearing – articulating surface.

CoCr=cobalt chrome; UHMWPE=ultra-high molecular weight polyethylene; HXLPE=highly cross-linked polyethylene; XLPE OxZr=oxidized zirconium; TiN=Titanium nitride; DLC=diamond-like carbon; CP-Ti=commercially pure titanium; NCD=nanocrystalline diamond; Cu=copper; Ti6Al4V=titanium alloy; NSD=nanostructured diamond.

cup,” “titanium nitride hip,” “titanium nitride joint,” “MITCH PCR,” “sapphire hip,” “aluminum oxide hip,” “HMU-CVD,” “SMS-CVD,” “P25-CVD,” and “carbon composite hip.” After removal of duplicates, this search returned 187 unique articles. For the most updated review, studies published from January 2015 and later (and more recently than 2005 in the case of the Cambridge cup and MITCH-PCR search terms) with full text in the English language were selected for further review. Animal studies, abstracts from meetings, case reports, materials science or computer model articles with focus only on molecular structure without tribological data, review articles, articles with sole focus on non-hip joint arthroplasty, studies that discussed metal-on-metal (MoM) bearing surfaces due to the current controversies were excluded. After these exclusions, 127 articles were reviewed for relevance. Reference lists of these publications were also reviewed and articles were included when appropriate. A total of 46 were selected for full analysis. Of these articles, studies with non-clinical or limited yet encouraging clinical data were focused on.

3. Results

3.1. Innovations in ceramics

The favorable tribology of ceramics as a THA bearing surface has made them an attractive option compared to earlier implant designs that were fraught with issues related to durability and survivorship.¹⁴ Traditionally, ceramic components were composed of alumina and zirconia, with alumina being more common. Ceramics are biologically inert, have a very low coefficient of friction and improved lubrication and wettability properties making them a promising orthopaedic bearing surface.¹⁵ Multiple studies have demonstrated the advantageous wear characteristics of ceramic-on-ceramic surfaces, with *in vitro* studies demonstrating up to two to three orders of magnitude in improvement of wear rates between ceramic-on-ceramic and standard cobalt-chrome (CoCr) on conventional polyethylene.^{16,17}

Although alumina and other ceramics were selected as bearing materials due to their superior wear properties, scratch resistance and hardness, they were found to be brittle and predisposed to fracture.¹⁴ To combat this, newer generation composite ceramic bearings such as Biolox Delta (Ceramtec, Plochingen, Germany) have incorporated zirconia as well as chromium oxide, yttrium and strontium to prevent crack formation and propagation.⁵ Fractures of ceramic implants are rare events, and reports of incidence vary in the literature. It has been estimated that the risk of fracture over the implant lifespan is around 0.03–0.05% for femoral heads and 0.013 to 0.017% for ceramic inserts.¹⁸

3.1.1. Sapphire

Sapphire has been explored as a potential bearing surface given its many physical and mechanical similarities to alumina. These crystals, which contain 99.99% aluminum oxide, are placed in a vacuum at 2100° Celsius, and are then prepared from single crystal formations.¹⁹ These bearings were shown to be inert, have low friction, high wear resistance, and biologically compatible. In a small study, 5 patients received THAs that contained sapphire femoral heads and had good results at 1- and 5-year follow-up.^{20,21} Further clinical testing is needed in order to validate the widespread use of this bearing surface.

3.2. Innovations in metals

In an effort to reduce the rate of complications and improve the tribological characteristics of metal-on- polyethylene (PE) and MoM bearing couples, design changes are being implemented to decrease PE wear and metal ion release, as well as the coefficient of friction for articulation.²² Various coatings are being tested that can increase the surface hardness and smoothness of metal alloys and provide a non-metal interface, such as “ceramicizing” the femoral head with alumina composites, or titanium nitride.^{22,23} The benefits of diamond and diamond-like carbon are also being explored, as well as methods for changing the composition of the underlying metal alloy.

3.2.1. Titanium nitride coating

Titanium nitride (TiN) is a bioinert ceramic that is hard, scratch resistant and has a low coefficient of friction; it is being explored as a coating on titanium alloy femoral components in order to potentially improve wear resistance, decrease the generation of PE wear particles reduce metal ion release,^{22,24,25} and provide increased surface area for cellular surface colonization and improved osseointegration.²⁶ Early wear simulations in a knee model were promising, which suggests that TiN-CoCr bearing couples had lower wear compared to other materials, except oxinium.²⁷

A recent review concluded that superiority of TiN over cobalt-chrome-molybdenum (CoCrMo) had not been proven, citing simulations that showed an increased wear compared to metal implants, as well as several retrieval analyses showing breakthrough of TiN-coated femoral head and total knee components.²⁸ They concluded that the parameters of the physical vapor deposition (PVD) process used to apply TiN to the underlying titanium alloy substrate have not yet been optimized. At present, the process allows contamination with niobium and formation of pinholes that can promote delamination.²⁹

In a recent review of ceramicized ball heads used in THA, it was found that TiN had been used to coat the heads of femoral components since the early 1990s, but data on clinical outcomes is sparse and conflicting, with a 95% survivorship at 11 years, but some have reported loosening rates to be from 25 to 44%.²² At this time, optimization of the PVD coating process to reduce the risk of delamination seems necessary before the true clinical utility of TiN-coated femoral heads can be assessed.

3.2.2. Silicon nitride coating

Silicon nitride (Si_3N_4) is a ceramic that is being tested as an alternate bearing surface. It has been shown to be harder than titanium alloy Ti6Al4V and a higher fracture toughness than aluminum oxide.^{30,31} Additionally, the wear rates have been shown to be lower, but the exact value is controversial.³¹

Another proposed advantage of this material is the potential for its wear particles to be resorbed *in vivo*, with one study that reported Si_3N_4 , while in its alpha phase, was found to be soluble in blood serum, but *in vivo* studies have yet to confirm this.³² The surface of Si_3N_4 has been shown to have a relatively low immune activation *in vitro*, which is a favorable finding for body acceptance and reaction to wear particles.³² Finally, Webster et al.³³ showed this material to have inherent bacteriostatic material, and was able to inhibit colonization of *Staphylococcus epidermidis* in *in vivo* studies when compared to titanium and polyetheretherketone (PEEK).

Moreover, Si_3N_4 has been tested as both a coating on an underlying metal substrate and as a standalone component. As a coating, a layer of Si_3N_4 was found to decrease the release of CoCrMo ions into surrounding fluid by a factor of 100.³⁴ Also, Si_3N_4 can be well-visualized radiographically, and is thought to favor osseointegration, but it is known to form oxides *in vivo* that might increase its surface roughness³¹; however, thermal treatment and the addition of yttrium and aluminum oxides have been shown to decrease this roughness.³⁵ Early wear tests of Si_3N_4 on Ti6Al4V were halted due to excessive wear, as well as noise generation.³⁶ But, testing was resumed with wear tests using diamond-like carbon (DLC) articulating against Si_3N_4 to decrease wear and noise, which found the Si_3N_4 -DLC bearing couple to have a 38% lower wear than a Si_3N_4 -aluminum oxide couple, a lower coefficient of friction than the Si_3N_4 -Ti6Al4V couple, and generated less squeaking.^{30,36} This proposed a new materials paradigm for THA components that consisted of a DLC coating on a Ti6Al4V femoral head and stem articulating against a Si_3N_4 acetabular cup.^{30,36} While this bearing couple was compelling, as it may combine the

benefits of ceramic-on-ceramic couples with a lower risk of fracture and squeaking, consistent wear rate and long-term durability data are needed for Si_3N_4 before it can be used as a standalone component. No clinical data is currently available, although a clinical trial of Si_3N_4 ball heads is currently under way.²²

3.2.3. Diamond-like carbon coating

Diamond-like carbon coatings have been used industrially to increase the corrosion resistance and lifetime of metals, like stainless steel. They have recently started to be considered as bearing surfaces in orthopaedics, as their high hardness and scratch resistance might decrease wear and the release of metal ions into surrounding tissues. Tribological studies have been promising, with the coefficient of friction of DLC-coated Ti6Al4V heads against Si_3N_4 found to be lower than that of the bare alloy by up to 150%.³⁰ Tribological performance of hydrogenated amorphous carbon (a-C:H) DLC-coated micro-dimpled prostheses revealed significant reduction in coefficient of friction when compared to CoCr-ceramic.³⁷ In addition, DLC-coated Ti6Al4V has been shown to be 2–3 times harder than the alloy alone, but less hard than SiN.^{30,36}

Biocompatibility testing of DLC coatings has been mixed. Linder et al.³⁸ demonstrated that DLC coated surfaces did not activate cells of monocytic lineage. Also, there have been concerns regarding the cytotoxicity of graphite nanoparticles, the wear debris that are formed from this type of bearing surface. Cell viability of both mouse osteoblasts and macrophages were affected in a dose-dependent manner from these debris, but when graphite nanoparticles exceeded 30 $\mu\text{g}/\text{mL}$, cell cytotoxicity was dramatically increased.³⁹

The few clinical applications of DLC have been marked by failure, with inferior survivorship in comparison to aluminum oxide heads at 8.5 years and coating delamination likely due to *in vivo* dissolution of a silicon-containing substrate-adhesion layer.⁴⁰ Further study of multilayer DLC with focus on substantiating substrate adhesion is necessary before more clinical trials are justified.

3.2.4. Nanocrystalline diamond

Nanocrystalline diamond (NCD) coating is grown on selected bearing surfaces via chemical vapor deposition. As with DLC, NCD has demonstrated great biocompatibility in the *in vitro* settings.⁴¹ In a simulator study, Si_3N_4 bearing surfaces coated with NCD underwent five million testing cycles, which equates to approximately five years of use of a THA, and there was no cracking, delamination, or squeak encountered, and wear rates were found to be superior to fourth generation ceramic wear rates.⁴³

3.2.5. Alumina coating

To combine the hardness and scratch resistance of alumina femoral heads with the lower fracture risk of metal alloys, there has been a focus on ceramicized metal femoral heads. Research has been underway since 2015 to optimize production of an alumina-coated Ti6Al4V surface with the goal of using it for both femoral and acetabular components.⁴⁴ The coating consists of an outer aluminum oxide layer to serve as a bearing surface, deeper alumina layers, and an inner aluminum-titanium (Al_3Ti) interface layer between the coating and the substrate. The first in a series of experiments showed high hardness and good adhesion, as well as identifying that coatings containing thinner interface layers were more resistant to cracking.⁴⁴ An unrelated experiment coated the same Ti6Al4V alloy with an aluminum oxide/yttria-stabilized zirconia composite (Al_2O_3 -40wt%8YSZ), and the ceramicized surface was found to be 2.5 times harder than bare alloy, with 253 times better wear resistance and a lower coefficient of friction against an aluminum ball⁴⁵; however, the composite showed

Table 1
Innovations in metals.

Author	Type of study	Level of evidence	# of patients	# of hips	Type of implant	Parameters assessed	Timing of evaluation	Protocol	Salient findings
Łapaj et al. ²⁹ 2015	Retrieval analysis	III		11 femoral heads	-TiN-coated TiAl6V4 femoral heads articulating with PE liners	-Quantification of lesions of coating -Surface roughness -hardness -elastic modulus -adhesion strength		-time of implantation 34d to 56 months	-dislocations are a cause of scratching of TiN coatings. -coating defects present in all implants; third-body wear seemed to play a role. -in implants with Nb droplet contamination, defect SA was higher. Coating adhesion strength was lower in these. -No correlation between implantation time and defect quantity or SA was found. -PVD process still imperfect, seems to allow for Nb and Ti contamination of TiN as well as pinholes and small regions of delamination. -coating fragments that crack can become third bodies. -Authors compared their results to alumina and CoCrMo, found better resistance to roughening than CoCrMo and worse than alumina.
Prachar et al. ²⁶ 2015	Cell biology/ bench research	V				-Colonization of surface by cells at 48h		-Pure Ti, Ti6Al4V, Ti35Nb6Ta, CoCrMo with TiN or ZrN coatings via PVD. -cell line was osteosarcoma	-lowest colonization values seen with TiN- or ZrN-coated CoCrMo. -blasting of surfaces increased roughness and caused lower colonization SA. -TiN-coated surfaces had greater colonization SA than ZrN. -Substrate: ZrN— Ti35Nb6Ta was highest in ZrN group, TiN-Ti6Al4V in TiN group. -Model to optimize for low porosity developed.
Ganapathy et al. ⁴⁵ 2015	Basic Science (Materials and Wear Testing/ Analysis)	V			-Ti6Al4V substrate with Al2O3-40wt% 8YSZ coating	-Wear rate -Hardness and microhardness -Optimal parameters for plasma spray application		-Plasma spray application process used	-Ti6Al4V against an alumina ball has a coefficient of friction of 0.454, wear of 3.75×10^{-4} mm ³ /Nm. -The composite coating has a wear rate of 1.48×10^{-6} to 375.00×10^{-6} mm ³ /Nm, better than alumina and SiC coatings. It's 2.5 times harder than bare alloy and has 253 x better wear resistance. -Composite showed some chipping and cracking, but less than the alloy.
Khanna et al. ⁴⁴ 2015	Basic Science (Materials Testing/ Analysis)	V		optimize	New paradigm proposed, with alumina coating on Ti6Al4V stem and cup.	-Hardness -Characteristics of the interface layer		-Cold spraying to apply Al on Ti6Al4V, then heat treating to promote adhesion via an Al3Ti layer, then micro arc oxidation to create a dense alpha alumina layer.	-Good adhesion found at Al3Ti interface; thinner interface layer less prone to cracks. -Composite is harder than the alloy

Table 1 (Continued)

Author	Type of study	Level of evidence	# of patients	# of hips	Type of implant	Parameters assessed	Timing of evaluation	Protocol	Salient findings
Khanna et al. ²⁴ 2016	Basic Science (Materials Testing/Analysis)	V			Continuation of previous study with alumina coating on Ti6Al4V	-adhesion			-MAO times must be longer to produce more alpha rather than gamma alumina (better wear resistance), but this is more expensive.
						-Optimization of MAO parameters for creation of dense alpha alumina layer.		-Similar to prior study: cold spray application of Al to Ti6Al4V, then MAO without intervening heat treatment. Outer layer then abraded to reveal dense alpha alumina layer	-Increased MAO time is expensive, and required to form more alpha alumina.
						-characterization of materials			-Increased pulse frequency was attempted; however, given cracking, 500 Hz found as optimal frequency.
						-hardness			-Reaction layer demonstrated good adhesion
Choudhury et al. ³⁰ 2017	Basic Science (Materials and Wear Testing/Analysis)	V			-Multi-layered N-doped DLC with Zr interlayers on Ti6Al4V discs -Si3N4 cups	-adhesion of reaction layer			-No toxic pure Al remained at the surface -Vickers hardness of 1900 HV
						-Surface properties (hardness, elastic modulus, roughness)		A solution of foetal bovine serum and deionized water containing gamma globulin powder was used as a lubricant for tribological experiments	-Hardness of DLC-coated Ti6Al4V is about 2–3 x that of Ti6Al4V, with a higher elastic modulus.
						-tribology (wear, coefficient of friction)			-Surface roughness of DLC-coated alloy and alloy were similar
									-CoF of high-DLC-content coated alloy was lower (in some samples by 150%) than uncoated alloy, which has a variable CoF
Pettersson et al. ³⁴ 2016	Basic Science (Materials Testing/Analysis)	V			-Silicon nitride coatings with various N/Si ratios	-dissolution rate of silicon nitride coatings			-DLC-Si3N4 pair less likely to have acoustic emissions than Ti6Al4V-Si3N4 pair, and showed less Si3N4 wear than the bare alloy.
						-Amount of CoCrMo ion release with and without SiN coating			-All low-DLC samples delaminated, none of the high-DLC samples did.
Choudhury et al. ³⁷ 2015	Basic Science (Materials and Wear Testing/Analysis)	V			-hydrogenated amorphous carbon (a-C:H, a DLC)	-Coefficient of friction		-a-C:H and t-C:H surfaces were either dimpled or not dimpled and articulated against ceramics	-SiN coatings were found to decrease the dissolution of CoCrMo ions into the surrounding fluid by a factor of 10 ² .
									-Dissolution rate of CoCrMo was found to be 0.7–1.2 nm/d, whereas the various SiN coatings dissolved at rates between 0.2–1.2 nm/day
					-tetrahedral amorphous carbon (t-C:H) -CoCr	-Roughness			-non-dimpled a-C:H had the lowest CoF, followed by dimpled a-C:H.
						-Debris particle diameter validating			-Dimpled stainless steel had the highest CoF, followed by non-dimpled CoCr.
Ghosh et al. ⁶⁴ 2015	Basic Science (Materials and Wear Testing/Analysis)	V			-Microdimpled DLC on Ti6Al4V	-CoF		-Osteoarthritis-oriented synovial fluid (OASF) and bovine serum (BS) were compared as lubricants	-a-C:H exhibited low surface roughness and generated wear particles of large diameter.
						-hardness			-DLC samples were harder and exhibited better lubrication with poor adhesion to substrate

evidence of cracking. Continued materials science study to ensure durable coatings and long-lasting adhesion between coating and substrate are necessary.

3.2.6. Copper alloys

Wang et al.⁴⁶ examined the hardness, coefficient of friction, and wear rate of commercially pure titanium (CP-Ti) in comparison to

Ti6Al4V and copper alloys of each (Ti5Cu and Ti6Al4V5Cu), and found that the wear resistance and hardness of each of the copper alloys were higher than their titanium counterparts, and coefficients of friction of the copper alloys against ZrO₂ were lower. Thus, Ti6Al4V5Cu was the hardest surface and had the lowest coefficient of friction.⁴⁶ To the best of our knowledge, copper alloys have not yet appeared in other tribological or clinical studies. Their

Table 1 (Continued)

Author	Type of study	Level of evidence	# of patients	# of hips	Type of implant	Parameters assessed	Timing of evaluation	Protocol	Salient findings
Choudhury et al. ³⁶ 2016	Basic Science (Materials and Wear Testing/Analysis)	V			-Microdimpled Ti6Al4V			-Cr interlayers were used in the DLC samples	-Microdimpled Ti6Al4V had a lower CoF than non-dimpled Ti6Al4V by 16%; DLC-coated and dimpled surfaces had a 33% lower CoF
					-Bare Ti6Al4V	-wettability -residual stress			
					-Multilayer DLC on Ti6Al4V and bare Ti6Al4V articulating against Si3N4	-Hardness		-Bovine serum used as lubricant	-DLC-Ti6Al4V was harder than bare Ti6Al4V and less hard than the Si3N4 ball it articulated against
						-elastic modulus		-Cr-doped multilayer DLC used with Cr-Cr ₂ N base layers	-Bare Ti6Al4V on Si3N4 wear test was stopped early due to excessive wear of both surfaces and noise generation; wear of DLC discs was less but still significant for several of the DLC samples -Wear of DLC on Si3N4 was 38% lower than that of an Si3N4/Al ₂ O ₃ couple as found by these authors in a previous study
Maru et al. ⁴³ 2015	Basic Science (Materials and Wear Testing/Analysis)	V			-Nanocrystalline diamond on Si3N4 substrate femoral heads	-wear -Wear		Bovine serum media	-Wear rate of 0.02mm ³ /Mc of wear test was found for the NCD–NCD tribocouple. This is on the same order of magnitude as alumina–alumina couples in the most recent literature. -No extraneous noise (e.g. squeaking) was generated
					-NCD acetabular liners	-Surface characteristics (e.g. roughness) -Microstructure			
Wang et al. ⁴⁶ 2015	Basic Science (Materials and Wear Testing/Analysis)	V			-CP-Ti and Ti6Al4V alloy			-ZrO ₂ was used as the wear test surface	-Ti ₂ Cu was formed as a component of the Ti5Cu alloy
						-Composition		-Bovine serum was used as a lubricant	-Wear resistance increased as follows: CP-Ti < Ti-5Cu < Ti6Al4V < Ti6Al4V5Cu -Adding copper increased wear resistance and hardness of both CP-Ti and Ti6Al4V
						-Hardness			-Coefficient of friction was lower in Ti5Cu than CP-Ti as well as Ti6Al4VCu < Ti6Al4V
						-Coefficients of friction and wear compared to CP-Ti and Ti6Al4V			-Ti5Cu and CP-Ti had better wear resistance; Ti6Al4VCu and Ti6Al4V did not differ much. -Ti6Al4VCu was the hardest surface with the lowest coefficient of friction

CoCr=cobalt chrome; OxZr=oxidized zirconium; TiN=Titanium nitride; CoCrMo=cobalt-chrome-molybdenum; SiN=silicon nitride; DLC=diamond-like carbon; Al3Ti=aluminum-titanium; CP-Ti=commercially pure titanium; NCD=nanocrystalline diamond; Cu=copper; Ti6Al4V=titanium alloy; NSD=nanostructured diamond; ZrN=zirconium nitride; Al₂O₃-40wt%8YSZ=alumina oxide yttria stabilized zirconia.

Table 2
Innovations in component design.

Author	Study type	Level of evidence	# of patients	# of hips	Type of implant	Parameters assessed	Timing of evaluation	Protocol	Salient findings
Bennett et al. ⁶¹ 2014	Prospective RCT	II	60	60	-SR71 carbon fiber composite stem -Stability Ti6Al4V stem	-BMD -HHS, VAS	-2 months, 9months, 18 months, 3 years, and 10 years post-op	-Stability stem is cementless	-41 completed 10-year follow-up -No difference in clinical outcome scores -2 SR71 patients underwent revision -1 revision in the Stability group -Greater post-op increases in BMD in the SR71 group in Gruen zones 1 and 7; greater BMD increase in Gruen zone 3 in Stability group -good apposition and fixation to bone with Ha coating
Brooks et al. ¹⁰ 2010	Retrieval	III	50 (all female)		-HA coated Cambridge cups (24) -identical Cambridge cups with dissolved HA coating (26)	-wear particle generation -periprosthetic tissue reaction - thickness of remaining HA coating	12 total implants retrieved post-mortem	-patients had subcapital fractures -evaluation was histological	-HA coating thickness decreased with time; all specimens under 53 months still had intact HA coating -significantly less bone apposition was found with non-coated implants -CF and polymer particles seemed to generate a mononuclear response without evidence of osteolysis -17 completed 5y follow-up
Field et al. ⁹ 2005	Prospective RCT	II	50 (all female)	50	- HA coated Cambridge cups (24) -identical Cambridge cups with dissolved HA coating (26)	-Clinical outcomes (Charnley-modified Merle d'Aubigne-Postel score, mean Barthel index) -BMD	-5-year follow-up of Cambridge cup -Follow-ups at 6wks, 6mos, 1y, 1.5y, 2y, and 5y post-op -DEXA scans at 6wks, 3mos, 6mos, 1y, 1.5y, and 2y post-op	-All patient had subcapital femoral fractures amenable to treatment via hemiarthroplasty	-The patient population was osteoporotic, which is not representative of all THA patients. -Clinical outcomes increased with no variation between groups -4 revisions in the dissolved HA coating group -Overall average BMD fell over 2 years post-op
Field et al. ¹¹ 2006	Prospective RCT	II	11 (all female)	11	- HA coated Cambridge cups (5) -identical Cambridge cups with dissolved HA coating (6)	-Post-operative changes in bone mineral density	-DEXA analysis at 6 months in 2 patients, 1 year in 1 patient, and 2 years in 8 patients	-11 consecutive patients selected from larger study	-BMD decrease was less than that reported in the literature for titanium acetabular cups
Field et al. ⁸ 2012	Prospective RCT	II	25	25	-MITCH-PCR cups -Uncemented Accolade (Ti) stems -cemented Exeter (SS) stems -Alumina femoral heads	-Cup migration -Percent survival -Clinical outcomes (OH, HHS, EQ-5D)	3-year follow-up	-posterior approach -uncemented	-2 patients had squeaking hips; 1 underwent revision for squeaking and the other experienced spontaneous resolution of noise -3 revisions for pain -96% 3YS -88% 4YS -Loosening in 5/19 patients with Accolade stems; thought to be due to Ti wear debris -Clinical outcomes improved post-op

use has likely been limited due to fear of the well-known cytotoxic effects of copper ions; however, their superior tribological performance may warrant further exploration with metal ion diffusion and biocompatibility studies involving human cell lines. A recent study of human osteosarcoma cells incubated with various titanium-copper alloys demonstrated no increase in cytotoxicity with increasing copper content, and no difference in cytotoxicity between the copper-containing alloys and CP-Ti.⁴⁷ More detailed results are shown in Table 1.

In summary, many of the recently developed coating materials are subject to the same disadvantages, which are poor adhesion to the metal substrate comprising the femoral head. Moreover, DLC and TiN exemplify this limitation; in addition, NCD-on-NCD wear data is encouraging, but limited. More consistent and cost-effective manufacturing (particularly for alumina coating), along with more reliable wear simulation data, are necessary before a complete understanding of the utility of these materials can be reached. Finally, increasing the copper content of titanium alloys improves tribology, but biocompatibility must be assessed.

3.2.7. Compliant bearings

This unique type of bearing has attempted to mimic the mechanical properties of normal articular cartilage, which would allow for more optimal lubrication conditions. The main focus of research on compliant bearings, or “cushion bearings” has been on polyurethane compounds, largely polycarbonate-urethane (PCU). The flexible and hydrophilic properties of this material allow for a thick fluid film to develop, leading to a separation of the bearing surfaces with theoretical reduction in wear and lower friction.⁴⁸ Tribological studies have validated polyurethane cups to be extremely low friction when compared to UHMWPE, but there has been concerns regarding the amount of creep and subsequent head penetration that the material may allow.⁴⁹

Wear rate analysis of PCU cups with CoCr head in a simulator study of 8 million cycles revealed a wear rate below described values for polyethylene cups. Additionally, there were fewer wear particles generated, and they were also noted to be larger in size with a theoretical decrease potential for osteolysis.⁵⁰ Impressively, wear particle generation was noted to be 5–6 orders of magnitude lower than HXLPE. This study was followed up with a 20 million cycle simulation to evaluate for long term wear, and the improved wear characteristics of PCU were maintained with no evidence of fatigue damage of the materials.⁵¹ In a sheep model study with 4 year follow up, no change in wear performance was noted during follow-up; however, 4 out of 36 acetabular components debonded from the cement mantle.⁵²

Commercial hip implants that utilize a PCU have been available on the market, mainly in Europe. Tribofit (Active Implants Corporation, Memphis, TN) is one such system that employs a PCU acetabular liner that can be inserted into a metal backed cup that is subsequently press fit or directly inserted into bone. Clinical trials of this implant are currently limited to studies with relatively short follow-up, however, they demonstrated this novel bearing surface to be an effective and safer alternative to traditional bearing surfaces.^{53,54} When compared to MoM THA at 27-month follow-up, patients implanted with Tribofit had similar clinical outcomes, but with significantly lower serum metal ion levels.⁵⁵

Also, some trepidation exists regarding implantation technique, whether the PCU liner is inserted directly into bone or is metal backed. Cadossi et al.⁵⁶ compared 96 patients receiving compared bipolar hemiarthroplasty or non-metal backed PCU-containing THA for treatment of displaced femoral neck fractures, finding PCU-group patients displayed higher pain scores and 84.1% 3-year implant survivorship. Significant cup dislocation and back-sided wear along the bone-implant interface have been found in multiple cases.^{56–58} Given the inherent elasticity and compliance of PCU, abrasive wear can occur against the patient's native acetabular bone when the component does not have a metal backing. Although compliant bearings have promising wear properties, long-term data is lacking and its optimal implantation technique is uncertain.

3.3. Innovations in component design

The hypothesis that implants that mimic the human acetabulum more closely may have better longevity *in vivo* has driven several important advances over the past three decades. Components that are too stiff may cause loosening as a result of bone resorption secondary to stress shielding, but components that are too compliant can generate high volumes of wear debris; this can lead to loosening as a result of the debris related osteolytic immune response. Implant shape might explain similar distortions in the native bone as the stresses of weight-bearing are distributed differently after THA.^{59,60} Carbon-fiber-reinforced composites might be one answer to the search for substances with near-bone elastic moduli and mixed long-term clinical outcomes.⁶¹ Meanwhile, finite element analysis (FEA) has shown promising results for horseshoe-shaped acetabular cup designs over the traditional hemispheric cups, with respect to the distribution of stress and expected postoperative changes in bone mineral density.^{7,59}

3.3.1. Horseshoe cups

The Cambridge cup, which is shaped like a horseshoe with six spikes on the back, consists of an inner UHMWPE bearing surface and an outer carbon-fiber-reinforced polybutyleneterephthalate (CFR-PBT) shell. Hydroxyapatite (HA) coating has been tested as a means to combat excessive surface smoothness of horseshoe-shaped acetabular cups designed to mimic the native acetabulum.^{8–10} In a retrieval analysis, 12 Cambridge cups demonstrated good apposition to bone and fixation in the group with hydroxyapatite coating, and significantly less in the HA-dissolved group. Additionally, DEXA studies in 11 selected patients found that there were overall decreases in bone-mineral density (BMD) after THA, but the average decrease was of smaller magnitude than that reported in the literature for titanium acetabular components.¹¹ Also, histologic analysis of periprosthetic tissue revealed a mononuclear inflammatory response to carbon fiber and polymer particles without osteolysis.¹⁰

An updated version of the cup, the MITCH-PCR cup, altered the spike distribution and changed both the material and the role of the carbon-fiber-reinforced composite; moreover, it is horseshoe-shaped and is comprised of a CFR-PEEK bearing surface in a HA-coated titanium shell,¹² and was designed to articulate with large ceramic femoral heads. Field et al.⁸ performed a randomized-

Table 2 (Continued)

Author	Study type	Level of evidence	# of patients	# of hips	Type of implant	Parameters assessed	Timing of evaluation	Protocol	Salient findings
									-2 cups migrated

BMD = bone mineral density; HA = hydroxyapatite; HHS = Harris hip score; CF = carbon fiber

controlled clinical trial that evaluated 25 MITCH-PCR cups articulating with alumina heads on either titanium or stainless-steel stems, and found that the 3-year survivorship was 96%, with 2 instances of squeaking, of which 1 required revision. It was also reported that the trial was confounded by the different stem types; 5 of 19 patients with the titanium stem experienced loosening.⁸ More detailed results are found in Table 2. Furthermore, FEA analysis has suggested smaller decreases in BMD will be seen with MITCH-PCR cups compared with Cambridge cups or hemispherical acetabular components, but further clinical data on the MITCH-PCR, Cambridge cup, or other horseshoe acetabular designs are needed.⁵⁹

4. Conclusion

This review sought to provide an update on the status of various materials and design initiatives for use in THA. Although some of the above mentioned alternate bearing surfaces have shown promising *in vitro* and early clinical data, they lack larger, long-term clinical trial results. Further research and innovation is needed to find the optimal bearing surface, especially to accommodate the trend of younger and more active patients undergoing THA. Implant longevity is of paramount importance if the clinical success of total hip arthroplasty is to be maintained.

Conflict of interest

None.

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