Focus On
Bearing surfaces in lower limb total joint arthroplasty

Introduction
More than 160 000 total hip and knee joint replacements are performed annually in England and Wales. This is exceeded by the US where over 600 000 are performed per year. These figures are expected to rise with an ageing population and wider indications for surgery. The issue of implant fixation is essentially resolved with comparable survivorship levels across joint prostheses. Failure still ensues, largely as a result of wear. Consequently, selection of a bearing articulation remains a topical subject.

An ideal bearing surface:4
• has a low co-efficient of friction.
• is resistant to third-body damage and wear.
• generates small amounts of wear debris.
• causes low cellular reactions to such wear debris.

Selection of an appropriate couple is paramount, in order to ensure the best clinical outcome for the patient. The properties of the most widely used materials will be explored in this focus article so that an informed opinion can be made.

Polyethylene
Polyethylene is a polymer consisting of long chains of the monomer ethylene (Fig. 1). It can exist in many different forms depending on density and the amount of branching. The first type of polyethylene used in modern joint replacement was ultra-high molecular weight polyethylene (UHMWPE) which was popularised by Sir John Charnley in the 1960s with his Low Friction Arthroplasty (LFA). Coupled with a metal bearing, UHMWPE provides a high rate of satisfaction, outcome and survivorship in both total hip replacement (THR) and total knee replacement (TKR).

One major disadvantage, however, is the generation of wear debris from polyethylene which can lead to aseptic loosening. Minimising wear is thus a key focus for development although there have been noteworthy catastrophic failures in the name of evolution. These include the incorporation of carbon fibres (Poly II) and gamma irradiation in air (Hylamer), both of which had better wear profiles in vitro but ultimately proved to be inferior to UHMWPE in vivo.5-9

The most significant advance in improving the wear properties of polyethylene is highly cross-linked polyethylene (XLPE); a modified form of UHMWPE that has a higher crosslink density. Although each implant company manufactures XLPE in a different way, there are common steps that make them reasonably comparable. These common steps include irradiation and thermal treatment.

Gamma ray or electron beam irradiation breaks down intermolecular bonds. Free radicals generated by this process promote crosslinking across multiple polymer chains thereby increasing density and strength. There is, however, a complex interplay between oxidation and irradiated UHMWPE. Oxygen may be found within polyethylene, located in either structural voids or within the body of the material, having diffused in from the atmosphere. Irradiation of such oxygen will generate oxygen free radicals which can reside in either the amorphous or crystalline regions of the polymer. Only 30% to 40% of UHMWPE is crystalline and oxygen free radicals found in this region remain relatively more stable than those in the amorphous region where oxygen can diffuse out. These ‘trapped’ oxygen free radicals can then cause long-term oxidative damage; this helps to explain the reports of early failure for Hylamer which was gamma sterilised in air.9

There is thus a need to improve oxidative stability; this can be achieved through two types of thermal treatment. The first is to anneal the irradiated material below its melting point, a process which preserves the crystalline nature of irradiated polyethylene.

Fig. 1
Polyethylene is composed of recurring units of ethylene

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but does not remove all free radicals; this may result in long-term oxidation. The second method is to melt the material, i.e. anneal the material above its melting point. Since the crystalline structure is also melted, this process almost eliminates any residual free radicals; however, a lower crystallinity content may occur which can impair the material’s mechanical properties.20

Short-to mid-term reports of these first-generation XLPE implants suggest that it is a safe and effective material. Digas et al11 reported their findings of two randomised studies using radiostereometric analysis at a five-year follow-up. In their first study, patients undergoing a unilateral cemented THR were randomised to receive either conventional UHMWPE or Durasul (Zimmer, Warsaw, Indiana) as their acetabular liner. In the second study, patients undergoing bilateral hybridTHR received either conventional UHMWPE or Longevity (Zimmer) as their acetabular liner. Both XLPE acetabular articulations were processed using electron-beam radiation with subsequent melt annealing. The steady-state wear rate was close to zero in the two study groups after two years although it continued at 0.06 mm/year for the conventional polyethylene groups at five years. This is clearly encouraging support for XLPE use although it is worth noting that the only case revised for XLPE use although it is worth noting that the only case revised for aseptic loosening was in the Durasul group. More recently McCalden et al12 published their findings, which again compared Longevity (Zimmer) XLPE to a UHMWPE acetabular liner. Over five years they noted a linear penetration rate of 0.003 mm/yr for XLPE and 0.051 mm/yr for UHMWPE. There were no reports of revision for aseptic loosening. Reports of implant fracture and osteolysis do exist with XLPE usage but these have been attributed to impingement and the design of acetabular shell,13,15 and suggest that XLPE is a safe material to use in THR.

The role of this first-generation XLPE in TKR is not yet clearly defined. In 2005, Ries16 wrote strongly in opposition to the use of XLPE in TKR. He noted that the hip and knee replacements were not comparable because of the differing forces that go through each joint. Namely, the knee is less conforming than the hip, which gives it a lower contact area and higher contact stresses. Although the contact area in a knee produces a compressive stress along the surface of the tibial insert, the roll-back exhibited in most primary designs changes the contact point to produce a net cyclical tensile stress. This has implications for clinical practice as, in vitro at least, crosslinking appears to decrease the ability of UHMWPE to resist crack inception and propagation under cyclical loading.17

Presently there are still only short-term reports of first-generation XLPE use in TKR. Hodrick et al18 performed a retrospective review of 200 consecutive primary TKRs and compared Durasul (Zimmer) with conventional UHMWPE at a mean follow-up of 75 months and 91 months, respectively. There were two patients in the XLPE group who had radiological evidence of lucencies, although neither underwent a revision procedure for loosening. There were no reports of implant failure; 20 patients in the control group had lucencies evident on plain radiographs and three patients required revision for loose tibial components.

Prospective randomised studies are clearly needed for TKR, although it may be that second-generation XLPE may surpass its first-generation equivalent, even before the latter has been given a fair chance to prove its worth. As annealed XLPE carries residual oxygen free radicals that may promote long-term degradation, and because melted XLPE has possible deleterious mechanical properties as a result of its lower crystalline content, research has focused on maintaining the mechanical properties of XLPE while simultaneously reducing the free radical content trapped in the crystalline layer. The strategies for accomplishing this include sequential irradiation and annealing and blending with vitamin E (α-tocopherol).

X3 (Stryker Howmedica Osteonics, Mahwah, New Jersey) is a second-generation XLPE where the polyethylene receives a high dosage of radiation cumulatively instead of during one event; annealing is performed after each dose.19 E-Poly (Biomet, Warsaw, Indiana) is another second-generation XLPE but is stabilised with vitamin E; this acts as an antioxidant to scavenge free radicals. It is also annealed, which may offer a favourable mechanical profile to act as a bearing surface in knees while resisting oxidation.20 Since both these materials have only recently become available for clinical use, there is currently little objective data to support their use despite favourable in vitro reports.

The use of soft materials other than polyethylene is limited, although polycarbonate polyurethane appears to show promise by acting more as a compliant buffer. It is a hydrophilic material that appears to encourage the development of synovial fluid within the joint space and offers mechanical properties similar to that of native cartilage. Wear particles, when produced, are much larger than with UHMWPE, metal or ceramic although in vivo animal studies show favourable gross wear properties. This suggests that polycarbonate polyurethane may have a role to play as an alternative soft bearing surface.21-23

Metals
The most widely used metal alloy in joint replacement is cobalt-chrome as it provides the best compromise between stiffness, strength, resistance to corrosion and biocompatibility. It is a successful bearing surface when used with polyethylene although the issue of wear with UHMWPE has led to a resurgence in the use of metal-on-metal (MOM). This latter articulation is not a new concept but has become more popular since the advent of modern hip resurfacing arthroplasty.

The main advantage of a hard-on-hard bearing is a theoretical reduction in wear which, for THR at least, allows larger diameter femoral heads to be used. This has been demonstrated even with the first-generation MOM THR, where long-term results show that it was the design of implant that contributed to failure rather than wear, which was actually quite low.24 However, there are side-effects which have decreased the use of MOM; these include metallosis, aseptic lymphocytic vasculitis associated lesions (ALVAL), pseudotumours and chromosomal aberrations. There is significant overlap in the literature regarding the difference between metallosis, ALVAL and pseudotumours. It is likely there is a spectrum of change in response to the deposition of cobalt-chrome wear particles in periprosthetic tissues,25 which may either be a toxic reaction to an excess of particulate metal wear debris or a hypersensitivity reaction to a normal amount of metal debris.26 The risk factors which promote the
generation of wear debris in resurfacing arthroplasty include female gender, a small size of femoral component, a high abduction angle and obesity.27

A further main concern with MOM couples are the systemic effects of raised levels of metal ions which may be more pronounced in THR than resurfacing arthroplasty28 although the use of modular femoral heads may be an important risk factor for this. It is accepted that raised levels of cobalt and chromium can cause toxicity although harmful systemic effects have not yet been experienced following hip replacement.

Ceramics
Ceramic is the other 'hard' material used as a bearing surface. It is harder than metal with a lower rate of wear, is more wettable and produces inert wear debris. This avoids the deleterious side-effects of metallosis and its associated sequelae when coupled with itself. In contrast, it is more expensive, carries a risk of component fracture and a proportion of patients with ceramic-on-ceramic (COC) joint replacements notice squeaking.

As with polyethylene, there has been an obvious evolution with ceramic technology, the fourth generation of ceramics now being in existence. First-generation implants were used in the 1970s and 1980s. The sintering process which was then used produced large crystals that reduced an implant's density and increased the incidence of component fracture and crack propagation. Improvements in strength and microstructure led to second-generation ceramics being used after 1988. During this period, it was noted that the addition of oxides such as MgO could limit grain size during the long sintering process, thereby further improving its mechanical properties.29 Hot isostatic pressing (HIP) is a characteristic processing feature of third-generation ceramics which was first used in 1994. HIP is performed at lower temperatures than are used for sintering so that the speed of grain growth is limited; this grain size and increases material density.30

There are two types of ceramic which are used at THR, alumina and zirconia. Until recently, implants have been composed of one type only but fourth-generation implants, which include both types may capitalise on the perceived advantages of each.31 At first, alumina was used although the incidence of femoral head fracture of the early implants was as high as 13.4%,32 third-generation ceramic is now reported to have a lower rate of fracture of only 0.004%.33 Seminal work by Sedel et al34 demonstrated better survivorship of alumina hip prostheses in patients younger than 50 years of age, suggesting that COC THR may be specifically indicated for patients in this age group. Zirconia is the other type of ceramic that has historically been used within arthroplasty surgery. Early simulator studies were promising with lower rates of wear than alumina.35 However, catastrophic wear in combination with ceramic36,37 led to the recommendation that zirconia should be articulated only with polyethylene. Even with polyethylene however, zirconia displayed an inferior wear profile than alumina in vivo via mechanisms that appear to be related to phase transformation and altered surface roughness.38,39 Zirconia was consequently withdrawn from the market.

Ceramic as a bearing surface in TKR has not yet reached the popularity seen in THR, which may be attributable to the concerns regarding implant fracture. Nonetheless, there are favourable reports using the Bisurface knee system (Kyocera, Kyoto, Japan) which is an alumina femoral prosthesis.40

Combining differential hard bearing surfaces is also an area for development. John Fisher and colleagues have noted from simulator studies that the wear produced from ceramic-on-metal (COM) couples is 100-fold lower than with 28 mm MOM bearings; this is a consequence of the differential hardness of the bearing surfaces, smoother surfaces, improved lubrication, and a reduction in corrosive wear.41,42 This is clearly promising, with early in vivo work supporting low rates of wear and lower levels of metal ions than with MOM.43,44 Whether this will translate clinically to the ideal bearing couple remains unproven.

Metal/Ceramic hybrid
The issue of ceramic fracture may be solved by producing a metal-ceramic hybrid. Ceramics provide a hard bearing surface with a low rate of production of inert wear debris. The main opposition to their use is the risk of component fracture, as well as their cost. Coating a metal with ceramic is not worthwhile as the ceramic can crack, chip or peel, especially when damaged. This concern led to the development of Oxinium (Smith & Nephew, Memphis, Tennessee), a metal alloy that is super-heat-treated in order to oxidise the surface to a ceramic while retaining a metal-backed core.45 Although originally designed for use in TKR, Oxinium is now also being used as bearing surface in THR in combination with polyethylene. Low rates of wear in a young population appear to justify its use46 although mid- to long-term results are still required.

Conclusions
There have been numerous advances in bearing surface technology and the ideal couple has yet to be realised. Hard-on-hard designs have potential side-effects that may make surgeons cautious about their use although it is possible that new forms of polyethylene may obviate the need for such a couple.

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