

Current state and future of joint replacements in the hip and knee

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Joint replacements of the hip and knee are among the most clinically successful operations. According to figures compiled by the American Academy of Orthopaedic Surgeons, the number of primary total hip replacements performed in the USA was 220,000 in 2003. This was 38% more than in 1996 and this number is expected to rise to 572,000 (plus another 97,000 revisions) by 2030. The number of primary total knee replacements performed in 2003 was approximately 418,000 and is expected to rise exponentially with the increasing numbers of baby boomers and the aging population. Current research focuses not only on extending implant longevity, but also on improving function to meet the increased demands of today's patients, who are likely to be younger and more active than their predecessors two decades ago. Potential advancements in arthroplasty surgery include new, more wear-resistant bearing surfaces, porous metals to enhance osseointegration and replace lost bone stock, a clearer understanding of the biological processes associated with periprosthetic osteolysis, minimally invasive surgery and computer assisted surgery. Long-term studies are needed to establish the efficacy of these new technologies.

KEYWORDS: current • future • hip • joint replacement • knee

Modern total joint replacements are highly successful in treating pain and disability due to end-stage arthritis, but there are limitations to this technology. The ideal implant would be biocompatible, replicate normal hip function and last the patient's lifetime. Current implants have a finite lifespan and fail due to a variety of reasons such as wear, instability and infection. The heightened need for a solution for painful arthritic disorders, current emphasis on remaining physically active, better patient education and strong marketing by the implant companies have led to younger (<60 years of age) patients undergoing joint replacement earlier in their lifespan. An increasing number of these patients expect to lead high-demand, physically active lifestyles after their surgery. This will probably translate to more revision surgeries due to implant wear in the future. The outcomes of revision surgeries have improved but the complication rates are still much higher than the primary procedures. In a study on Medicare patients (1997–2004), Ong *et al.* quantified the projected economic burden of revision total hip

and knee replacements [1,2]. They found that unless some limiting mechanism is implemented to reduce the incidence of revision surgeries, the diverging trends in reimbursements and charges for total hip and knee arthroplasties indicate that the economic impact to the healthcare system will continue to increase. In this review, we will look at the latest research efforts in improving the longevity and function of modern-day implants.

Bearing surfaces

Bearing combinations include polymeric, metallic and ceramic materials. The various combinations in clinical use include metal-on-polyethylene (MoP) and ceramic-on-polyethylene (CoP) – so-called 'hard/soft bearings' – and metal-on-metal (MoM) and ceramic-on-ceramic (CoC) – so-called 'hard/hard bearings'. In an extensive review of clinical series published on implant survivorship, osteolysis incidence and bearing wear, Dumbleton *et al.* concluded that wear greater than a threshold of

0.1 mm/year appears to increase the incidence of osteolysis, and wear rates of current bearing surfaces are substantially below this value [3].

Hard/soft bearings

The traditional coupling of a cobalt chromium alloy femoral head and an ultra-high-molecular-weight-polyethylene (UHMWPE) liner had linear wear rates of 0.04–0.25 mm/year, with a typical value in the range of 0.1 mm/year. With its improved wear characteristics, highly cross-linked polyethylene (HXLPE) has become a popular bearing surface for hip replacements. Many studies have shown an improvement in wear rates ranging from 60 to 90% versus conventional UHMWPE [4–6] and a linear wear rate of approximately 0.01 mm/year has been reported with HXLPE [7,8]. Crosslinking of polyethylene improves the resistance to adhesive and abrasive wear. However, crosslinking adversely affects fracture toughness and ductility, and resistance to fatigue crack propagation. Crosslinking of UHMWPE using irradiation results in material that contains free radicals and can lead to oxidative degradation. To reduce or eliminate the free radicals, these materials are subjected to remelting above the melt temperature (e.g., Marathon[®], Depuy, IN, USA; Longevity[™] and Durasul[™], Zimmer Inc., IN, USA), or annealing below the melt temperature (e.g., Crossfire[™], Stryker Inc., NJ, USA) [9]. Heating above the melt temperature rids the material of free radicals but reduces crystal size, which decreases yield stress, ultimate stress and resistance to fatigue crack propagation. Annealing retains crystal size and structure and mechanical properties but the reduction in free radicals is less than with remelting. Second-generation crosslinked UHMWPE employs new methods such as multiple cycles of sequential radiation and annealing and Vitamin E doping [10,11]. These methods will hopefully maintain optimal crystallinity and mechanical properties and reduce free radicals and subsequent oxidation without the need for remelting. In a hip simulator study [12], the wear rate of vitamin E-stabilized crosslinked UHMWPE was approximately four to ten-times lower than that of conventional UHMWPE. The ultimate strength, yield strength, elongation at break and fatigue resistance of vitamin E-stabilized crosslinked UHMWPE were significantly higher than that of remelted crosslinked UHMWPE and were unaffected by accelerated aging. Other researchers have taken a different approach by altering the surface of UHMWPE to improve its tribological properties without affecting its mechanical properties. One group has developed a novel polyethylene-hyaluronan (HA) microcomposite for use in total joint replacements. They used HA to modify the surface of UHMWPE [13,14] and found that the microcomposite enhanced lubrication of the UHMWPE surface and improved its wear resistance. Although the tensile properties of the new microcomposites were not satisfactory, they postulated that the low remolding temperature throughout the manufacturing process resulted in poor intermolecular entanglement of the UHMWPE and was not caused by the HA. HXLPE for the

knee has been available since 2001 (e.g., the Durasul from Zimmer Inc.), but its use is controversial. The improved adhesive–abrasive wear resistance that has been observed in the hip may not translate to the knee, which is much less conforming and has a greater association with fatigue wear mechanisms. There have been very few clinical studies on the *in vivo* performance of HXLPE in the knee. One retrieval study attempted to compare HXLPE and conventional polyethylene (PE) and found no significant difference in surface damage between the retrieved Durasul and conventional PE tibial components, and that machine mark loss and abrasion were the predominant types of surface damage observed on both the components [15]. The main weakness in this study, which the authors acknowledged, was the very different *in vivo* durations of the two groups, with a much shorter one for the HXLPE group (range 4–27 months) compared with the conventional polyethylene group (range 4–196 months).

Ceramic-on-polyethylene bearings are the other hard/soft combination available clinically. They have shown on average a 50% reduction in wear compared with MoP bearings [16]. In a long-term study of 64 hips with alumina and UHMWPE that was sterilized in air, survivorship at 10 and 20 years was 95% and 79%, respectively, and the mean linear and volumetric wear rates were 0.034 mm/year and 28 mm³/year, respectively [17]. Newer CoP couplings using HXLPE will probably provide even better results. A potential problem with CoP bearings in the hip has been reported by Clarke *et al.* [18], who found a dislocation rate of 6.4 versus 0.9% in MoM bearings. This has been attributed to increased wettability of the bearing. The CoP coupling (using zirconia and UHMWPE) has also been investigated in the knee. Zirconia has higher strength and toughness compared with alumina and can be manufactured with virtually identical dimensions to a CoC design. Contemporary knee femoral components feature either 100% zirconia or metal zirconium treated with a 5- μ m thick zirconia surface (Oxinium[™], Smith and Nephew, TN, USA), but only the latter is currently US FDA-approved. Although laboratory studies consistently reported superior wear resistance for zirconia/UHMWPE combinations when compared with controls, there have been very few clinical studies on the use of ceramics in total knee arthroplasties, and these studies are mostly short-term reports. In knee simulation studies, Tsuakmoto *et al.* compared both CoC and zirconia versions of the BiSurface (Kyocera, Japan) knee replacement in a 6-station knee simulator [19]. Two types of UHMWPE were used, 3.5 Mrad and 7 Mrad; the authors found that zirconia and the 7 Mrad UHMWPE gave the best results with no measurable wear over the 5.5 million-cycle test duration. The same group reported a follow-up study [20] with a 10 million-cycle test duration and found no measurable wear for the same zirconia/7 Mrad UHMWPE combination. Other groups have performed knee simulator studies using oxidized zirconium with UHMWPE [21] and found that this bearing couple reduced polyethylene wear by 42% compared with CoC at 5-million

cycles. In a clinical study with probably the longest follow-up, Akagi *et al.* reported a 94% survival rate at 6 years in 223 consecutive knees replaced with a bisurface posterior-stabilized design with an alumina femoral component and UHMWPE [22]. In a short-term clinical study with a follow-up of 2 years, Laskin *et al.* conducted a randomized prospective study comparing an oxidized zirconium and CoC femoral component with UHMWPE [23]. They found a more rapid return of flexion and regaining of functional milestones in the oxidized zirconium group and postulated that this could be due to the highly polished surface.

Hard/hard bearings

Metal-on-metal (essentially cobalt–chromium alloys) hip replacements and resurfacing have regained popularity in recent years [24] due to the relatively low volumetric wear rates, the ability to use large heads (conferring greater stability and increased range of motion) and improvements in metallurgy. Simulator studies have shown overall wear rates ranging from 0.5–5 mm³/million cycles, with a higher run-in wear rate and a lower steady-state wear rate from 1 year onwards, ranging up to 1 mm³/million cycles [25,26]. Although this is substantially lower than conventional MoP bearings, MoM bearings actually produce a greater number of particles since the debris generated is in the nanometer size range. This debris has a high surface area, which could account for the relatively high rates of metal release into the surrounding tissues. Multiple studies have documented elevated levels of metal ions in the blood and urine of patients with MoM bearings [27,28] and these ions have been shown to cross the placenta, which does exert some modulatory effect on the transfer rate [29]. Although long-term studies on patients with first-generation MoM hip replacements used in the 1970s show no increase in the incidence of cancer compared with the general population [30], it is worrisome that some researchers have raised the possibility of increased DNA [31] and chromosomal changes [32,33] occurring in patients with MoM bearings implanted. These changes are not unique to MoM bearings and have been seen in MoP knee replacements [31] and MoP hip replacements [33]. As the wear particles are usually less than 500 nm, they are pinocytosed rather than phagocytosed; pinocytosis is generally not coupled to inflammatory cell responses (unlike phagocytosis). Instead, the small size and large numbers of metal particles predispose to electrochemical corrosion [34]. Several reports of early failures of contemporary MoM hip replacements have implicated metal hypersensitivity as a factor contributing to osteolysis and pain [35–37]. These studies show that MoM bearings are not immune to osteolysis and aseptic loosening, and that volumetric wear rate alone does not dictate the prevalence of osteolysis. Other factors such as the characteristics of the degradation products (such as size, shape and chemical form) are important in the determination of bioreactivity [35].

The other hard/hard bearing in clinical use is CoC. Zirconium oxide and alumina oxide are both in use and they are inert, stable and hard. In addition, they develop a surface protein monolayer

in vivo which helps decrease adhesive and abrasive wear. Alumina ceramics are reported to resist abrasive forces 30–40-times greater than those causing comparable damage to titanium and cobalt–chrome alloys. Wear of CoC bearings are even lower than MoM and vary from 0.025 to 10 µm per year, and in contrast to the biodynamic metallic wear products from MoM bearings, particles from various ceramic biomaterials are thought to be biostable and much less inflammatory [38]. However, CoC bearings are not immune to osteolysis. Historically, osteolysis and aseptic loosening have been reported in association with early designs of CoC bearings, particularly the Mittelmeier hip replacement [39]. In these hips, the acetabular component of the Mittelmeier hip prosthesis typically loosened and migrated into a vertical position, leading to edge loading and increased wear. When a MoM or CoC bearing becomes non-congruent during activity from reasons such as component malalignment or impingement, high bearing stress and localized bearing wear occurs and can manifest as stripe patterns on the head and rim of the liner. Recent short- to mid-term clinical studies of third-generation alumina bearings have shown promising results with little or no osteolysis [40–42]. One weakness of ceramic materials is their brittleness and decreased resistance to fracture. Factors implicated in ceramic fracture include poor material quality, large grain size, small femoral head size, residual internal stress, poor taper design and component malpositioning. Ceramics have evolved with the release of a third-generation ceramic in 1994 and this material is manufactured with the use of hot isostatic pressing to reduce grain size, limit grain boundaries and inclusions, increase burst strength and have better wear properties [43]. Ceramic components are now all proof-tested by loading, which sorts out bearings that are defective and have an increased risk of fracture. Although other authors have reported higher rates of fracture [44], an extensive review of ceramic hip replacements in 2003 revealed only 13 fractures after 5500 replacements [45]. There are two other potential problems unique to CoC bearings. One problem is that of squeaking, which can be permanent and very disturbing to the patient and has sometimes required revision to a different bearing surface [46,47]. Although squeaking has also been described in MoM bearings, it is usually transient and rarely necessitates a revision [48]. The exact cause is unknown but postulated to be related to stripe wear or transient loss of fluid–film lubrication. The other problem is that revision following a CoC bearing that has fractured is a very difficult undertaking, requiring extensive synovectomy and debridement to remove all the widely dispersed ceramic particles. This is also associated with high rates of rerevision and a survivorship of over 50% at 7 years [49].

Currently, the industry is moving towards zirconia-toughened alumina. This material is stronger than conventional alumina and allows manufacturers to thin down cup liners and use larger femoral heads. Even then, ceramic heads will not be as large as metal ones and several companies are now looking at silicon nitride, a stronger and tougher ceramic that might enable manufacturing of larger ceramic heads.

Newer bearings

A combination of ceramic-on-metal (CoM) has also been explored, and this coupling has shown lower friction, wear, and ion levels *in vitro* compared with MoM, with results similar to CoC bearings [50]. Short-term studies in 31 patients at 6 months revealed lower metal ion levels (cobalt and chromium) in those with CoM compared with MoM bearings. In an interesting development, the implant company Biomet Inc. (IN, USA) has teamed up with Diamicron Inc. (UT, USA) to develop a novel bearing surface in hip and knee replacements using polycrystalline diamond. This coating has the lowest coefficient of friction and is the hardest natural material known, but it is very costly and the product is currently in development and no human trials have started. Other companies are exploring diamond-like coatings on their implants as well.

Biological solutions to wear & osteolysis?

Currently, detection of osteolysis depends on radiographic methods, which have low sensitivity in the early stages of the disease. Researchers are currently working on several potential biologic markers of wear, including *N*-telopeptides of type-I collagen [51], chemokines such as IL-8, matrix metalloproteinases and osteoclast activators such as the RANKL [52–54]. Of particular interest is the role of RANKL, which is a soluble ligand inducing osteoclastogenesis and bone resorption, and its natural antagonist osteoprotegerin (OPG) in osteolysis. The majority of potential strategies toward the pharmacologic inhibition of osteolysis are directed at preventing bone resorption. In early clinical trials, treatment with bisphosphonates [MALONEY W; PERS. COMM.] or anti-TNF [SCHWARZ E; PERS. COMM.] has not been successful in mitigating established osteolysis. The RANKL antagonists may prove to be useful in the future as anti-resorptive agents for the treatment of osteolysis. Schwarz and colleagues have used a human monoclonal antibody against RANKL in Phase 2 and 3 clinical trials and have recently performed a study of OPG versus zoledronic acid (a bisphosphonate) in a murine model of osteolysis [55]. They found that zoledronic acid had limited effects while OPG completely prevented osteolysis.

Implant as a drug-delivery system

There has been recent interest in the effects of particulate wear debris on osteoprogenitor cells [56]. Studies using human and murine osteoprogenitors reveal that titanium, UHMWPE and polymethylmethacrylate (PMMA) particles at specific concentrations can inhibit bone cell viability, proliferation and downregulate markers of subsequent bone formation in a dose- and time-dependent fashion. In an *in vitro* study, Kim *et al.* showed that certain growth factors could mitigate the suppressive effect of titanium particles on mesenchymal stem cells [57]. They found that FGF-2 was the most effective enhancer of cellular proliferation and BMP-6

best promoted osteogenic differentiation. The concept of the implant as a drug-delivery system where osteoinductive or bone-friendly factors leach out of the surface to enhance osseointegration and thus longevity is a plausible and rational idea. In a rat model study, Peter *et al.* found that zoledronate (bisphosphonate), which was grafted to the HA coating of titanium implants, improved mechanical fixation [58]. A similar model was established in a sheep model by Stadelmann *et al.* [59]. In a rat femur osteotomy model, the local application of IGF-1 and TGFβ1 from a biodegradable coating was found to enhance osteotomy healing [60].

Porous metals

Hip

Cementless joint replacements are attractive in that they maintain bone stock and avoid another potential source of wear from bone cement debris. During the last 30 years, different porous designs and implant materials have been used to obtain cementless biological fixation in hip and knee reconstructive surgery. Cobalt chrome alloy, diffusion-bonded titanium and titanium plasma spray represent some of the most commonly used porous coatings to achieve bone ingrowth. Although these conventional porous coatings have demonstrated good-to-excellent clinical results, they possess some inherent shortcomings, such as low volumetric porosity (ranging between 30 and 50%), suboptimal frictional characteristics, higher modulus of elasticity relative to that of bone, potential bead dislodgement and entrapment in the bearing, leading to third-body wear and increased friction. Porous tantalum, a novel porous biomaterial, was developed under the trademark 'trabecular metal' by Zimmer Inc. (Warsaw, IN, USA). The key features include a structural biomaterial with interconnecting pores that is 80% porous, allowing approximately two to three-times greater bone ingrowth compared with conventional porous coatings and double the interface shear strength. The elastic modulus of tantalum (3 Gpa) compares favorably to subchondral (2 Gpa) or cancellous bone (1.2 Gpa) and yet its yield and ultimate strength is greater than cancellous bone or most of the bone graft substitutes [61,62]. In addition, tantalum has shown good corrosion resistance secondary to a stable oxidation layer. Tantalum is generally used as a surface coating or in areas of cancellous bone loss. Tantalum implants have gained an important role in revision surgeries, where it has significantly reduced the use of bulk allografts in cases with large bone defects. In the hip, the options include monoblock cups without supplemental fixation, revision shells with cemented liners, modular cups with standard liners, standard and custom acetabular augments and reconstruction cages. It is thought that the current generation of reconstruction cages do not provide biologic fixation and are subject to eventual loosening and breakage. Gross *et al.* have proposed a tantalum cup and reconstruction cage construct for extensive acetabular defects [63].

The cage spans the tantalum cup and a polyethylene liner is then cemented into the cage. In effect, this uses the tantalum cup as a bone graft in anticipation that bone ingrowth over time will relieve the stress on the cage reconstruction and prolong its survival. Paprosky *et al.* reported reliable short-term results with an interesting use of the tantalum cup in the management of severe acetabular bone loss in association with a pelvic discontinuity [64,65]. A tantalum cup with or without an augment was used to obtain fixation proximal and distal to the discontinuity, thus acting as an internal plate. Although early reports with the porous tantalum revision shell with or without the use of augments have shown good results regarding osseointegration and stability of the components and clinical outcomes [66,67], issues such as the current high cost of these implants and the lack of long-term data might temper the enthusiasm for their widespread use. Regenerex™ (Biomet Inc) and Tritanium™ (Stryker Inc.) are also engaged in this emerging technology of using porous metals as surface coatings and structural materials. Regenerex is a porous titanium construct with an average porosity of 67% and pore size ranging from 100 to 600 µm with an average of 300 µm. Tritanium Dimensionalised Metal has an average porosity of 65–70% and the Tritanium acetabular revision shell is now undergoing clinical trials.

Knee

Although tantalum implants are used in knee replacements [62,68], there are currently much less peer-reviewed data compared with the hip. The options available vary from a monoblock tibial component for primary cementless cases to a patellar button in cases where the patellar bone stock is poor. In our practice, we occasionally use tantalum cones during revision surgery as a bone graft substitute when large areas of cancellous bone are deficient. Radney *et al.* reported satisfactory and radiographic outcomes in nine patients who underwent revision knee with the use of tantalum cones [69]. Traditionally, the results of resection patellar arthroplasty, patellar allograft and revision with cemented patellar components for failures of a patellar prosthesis have been less than ideal. Two short-term studies have shown good results using the tantalum salvage patella [70,71], although the patella fracture rate was approximately 10–15% in both studies. This is acceptable taking into account the degree of bone loss and the fact that this was a salvage operation. The role of tantalum as a valuable addition to the armamentarium in treating severe bone loss in the knee can only be confirmed by long-term clinical studies.

Minimally invasive & computer-aided surgeries

Interest in minimally invasive surgical techniques for the hip and knee is growing and it has recently been estimated that, on average, 5% of procedures are currently being done with some form of minimally invasive surgery (MIS). This figure

is expected to double over the next few years. Our definition of a minimally invasive approach is one that minimizes soft-tissue (including the skin) trauma in order to improve postoperation rehabilitation and outcome.

Hip

Surgeons today are already performing hip replacements through smaller incisions than those several years ago and this appears to be a natural evolution of the procedure. Many patients are aware of the potential (yet unproven) benefits of MIS and still believe that a small skin incision is an important advance in the operation. The descriptions of MIS techniques are varied and include one or two incisions; the terminology can be as confusing for the laymen as it is for surgeons. For example, one group has described their MIS posterior approach as one in which: no incision is made in the tensor fascia; the gluteus maximus is split only 6 cm; the gluteus maximus tendon is not released; and the quadratus femoris is not released [72]. This is our standard posterior approach to the hip and we believe many other surgeons who perform surgery in the same way do not call it a MIS approach. Currently, although the majority of the published literature on MIS hip replacement is retrospective, underpowered and lack controls, the data do show that the outcome at 6 weeks' postoperation is no better than that achieved via a standard incision [73], except for the patient's psychological satisfaction, which diminishes in importance by 1 year [74]. The most popular and published among the different approaches is the mini-posterior approach. In three different randomized prospective studies comparing a MIS posterior versus a standard approach, there were generally no differences in the early postoperative or 1-year outcomes [75–77]. A consecutive series comparing 50 mini-posterior and 85 standard approaches showed that despite having the advantages of a lower mean body mass index and American Society of Anesthesiologists (ASA) score, the mini-posterior group had significantly higher rates of wound complications and component malposition [78]. The other technique that has been well-described is the fluoroscopic-guided, 2-incision approach that uses a small direct anterior approach for cup placement and a small posterior approach for the femoral component. The developers of the technique have had good experience [79,80] but the initial enthusiasm for this approach has been dampened by negative reports by other authors [81]. Some factors that lead to early failures include surgeon inexperience, low case volume and inexperience with MIS [82] but even in experienced hands, less than ideal outcomes have been reported [83–85]. A cadaveric study has challenged the premise that MIS minimizes soft tissue trauma [86]. Researchers compared the amount of soft tissue damage in ten hips that were replaced using the mini-posterior with ten hips that were replaced using the 2-incision technique and found that both techniques caused measurable damage to the external rotator muscles and abductors

and that the damage was greater in the 2-incision group. On the other hand, a recent clinical–biomechanical study looked at three groups of patients who had hip replacements by a standard posterior, MIS anterolateral or MIS posterior approach and found that the MIS groups had better *in vivo* kinematics and kinetics [87]. Another technique that is more commonly used in Europe is the MIS anterior approach [88,89] and the theoretical advantages are minimal or no damage to muscles or tendons. However, a recent cadaveric study showed that there was damage to the gluteus minimus (6%), tensor fascia lata muscle (31%) and direct head of rectus femoris (12%). With current techniques in hip replacement via all types of incisions, patients are recovering and walking faster and it is evident that MIS approaches are not uniquely responsible for this [73,77]. Improved preoperative patient education and perioperative pain management coupled with a comprehensive rehabilitation program have all contributed significantly to better early outcomes. There is no compelling evidence at present to recommend any one approach over the others.

Like MIS hip approaches, MIS knee approaches are more difficult and there are issues of surgeon's learning curve, patient preselection, reduced visualization of landmarks, instrumentation accuracy and the ability of implants to be compatible with MIS techniques (the wound can only be as small as the implant!). And similar to the hip, the definitions and terminology in the literature can be confusing but ultimately, the aim is to minimize trauma and improve outcome. The approaches commonly mentioned range from purely transcapsular to one in which a very small (<2 cm) extension was made into the midvastus or subvastus plane, depending on the local anatomy, as described by the originators of the approach [90]. A trademark has also been applied to one technique involving a short medial arthrotomy approach that extends to the superior pole of the patella (Quad-Sparing™ Total Knee Arthroplasty, Zimmer) but this approach has been questioned by findings from an anatomical cadaveric study, which found that the inferior edge of the vastus medialis obliquus consistently inserted at or near the mid-pole of the patella [91]. The authors concluded that any medial arthrotomy that extends more proximal than the midpole of the patella detaches a portion of the quadriceps tendon; thus, the term 'quadriceps sparing' should not be applied to any surgical approach with a capsular incision that extends more proximal than the midpole of the patella. The common factors in all of these approaches include using a reduced incision and mobile skin and soft tissue window, no patella eversion and modified instrumentation. As the techniques are currently evolving, most of the clinical data available come from short-term, nonrandomized studies and the results have been mixed. Most of the positive studies are first reports by originators of particular techniques or postoperative protocols [92–96]. Two well-designed prospective randomized trials comparing MIS and standard knee

replacements have shown no difference in early clinical and radiologic outcomes [97] and better early clinical outcome [98], respectively. While some authors have reported problems such as component alignment [99], others have not found malalignment to be a problem [100]. In summary, the available literature may suggest better early outcomes in terms of postoperative pain, range of motion and shorter hospital stays, but the advantage usually disappears by 6 months to 1 year with no distinct advantage accorded to either technique. Furthermore, there are many confounding variables in the assessment of the impact of MIS. MIS approaches are associated with a steep learning curve [101] and some authors have raised some ethical concerns about patients being involved in these new and unproven techniques [102]. At present, MIS approaches are best left in the hands of high-volume joint surgeons who are willing to invest time to learn and practice the technique; it cannot be recommended for the occasional joint replacement surgeon.

Computer-assisted surgical systems can be divided into active robotic, semi-active robotic and passive systems [103]. The most common example of a passive system is the computer navigation system, which aims to improve the surgical accuracy of joint replacements and allow intraoperative recording of kinematic data and range of motion. Navigation systems for the knee are more developed compared with the hip. Currently, the most popular navigation systems for the knee are image-free systems, which collect information needed for navigation through direct measurements of bony landmarks or through kinematic algorithms to determine joint centers. Thus, the system is only as accurate as the surgeon is in locating specific landmarks accurately and precisely. For example, a 7 mm anteroposterior error in identifying one of the femoral epicondyles would translate to approximately 5° of error in the transverse plane, which is unacceptable [103]. The senior author of this review was involved in a study that evaluated five alignment techniques (including four computer-assisted techniques and one traditional technique) to establish femoral rotational alignment axes on ten cadaveric specimens, and the orientation of these axes was recorded with use of a navigation system [104]. There were significant differences among surgeons with regard to their ability to accurately establish femoral rotational alignment axes and all techniques resulted in highly variable rotational alignment, with no technique being superior. On the opposing end, some clinical studies have found that navigation improves femoral rotation [105,106]. Other proponents of navigation have shown improvement in the postoperative mechanical alignment and a reduction in the number of outliers (implants with alignment error of > 3°) [105–108]. Currently, no long-term studies have shown that navigation improves functional outcome [109] and a recent randomized prospective trial comparing navigated and traditional knee replacements showed no difference in clinical outcome at 2 years [110]. It is difficult to improve on an operation with a very strong track record; it would require a sufficiently powered randomized trial with a

large number of patients who are followed up for a long period of time, before the subtle benefits of navigation can be convincingly proven. Currently, navigation for the knee does have several important roles:

- It is a valuable research tool that enables us to study the preoperative, intraoperative and postoperative kinematics [103,111] and also objectively assess ligament stability and balancing [112–114];
- It might be useful in situations where intramedullary jigs cannot be used on the femoral side, such as in cases with femoral deformity, retained hardware and patients with severe cardiopulmonary disease who tolerate fat embolism poorly [115];
- It might be useful if used in conjunction with a MIS approach where normal visual cues are lost from a smaller incision [116,117].

The caveat in this situation is that the surgeon must be competent and skilled in both the MIS approach as well as the navigation equipment. Some authors have also suggested the combination of computer navigation with MIS approaches to the hip [118,119]. Some recent studies have shown improved accuracy of cup placements with navigation systems [120–123]. Another potential benefit of navigation might be in hip resurfacing, where it might help in both cup placement and reduce the risk of femoral neck notching, especially for less experienced surgeons [120,124]. There are currently no long-term outcome studies available, and the technique itself is still evolving in terms of improvement to the tracking, imaging and calibration systems.

Expert commentary & five-year view

This is the decade where engineering, material science and biology converge. Current generations of joint replacements are designed to last much longer than their earlier counterparts.

Improvements in bearing surfaces including HXLPE, hard-on-hard bearings and novel combinations have reduced wear dramatically. However, the biological reactions to debris from new bearings must be clearly understood. The potential for biological solutions to wear and osteolysis, and the concept of the implant as a drug-delivery device to improve fixation, are also novel areas of research. Newer porous materials such as tantalum have increased our options for fixation and also in revision surgeries where they can be used to help replace lost bone. MIS approaches and computer navigation are relatively new and have not been validated by long-term outcome studies. However, we recognize their potential to improve functional outcome and as valuable research tools. Despite all the aforementioned advancements, we must remember that the joint replacement patient profile today is vastly different from that of 20 years ago, with the typical patient being younger and more active. The increase in activity level postoperation might negate the improvements in implant technology. Patients' expectations that have been raised by aggressive marketing campaigns will have to be tempered by the reality that, in the next 5 years at least, we do not see an implant on the market that will allow impact loading or vigorous athletic activities without a compromise in implant longevity.

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Key issues

- Current generations of hard/soft and hard/hard bearings have very low wear rates.
- New bearings lead to new biological reactions that have to be studied systemically and locally.
- Novel couplings such as ceramic-on-metal and a diamond-coated bearings are being studied.
- Potential biological solutions to osteolysis are directed at preventing bone resorption and they include nonimmunosuppressive, antiresorptive agents such as osteoprotegerin and RANKL antagonists.
- The novel concept of the implant as a drug-delivery system, where osteoinductive or 'bone-friendly' factors leach out of the surface to enhance osseointegration, is being studied.
- Novel biomaterials such as tantalum have improved our options for enhancing implant osseointegration and also in revision surgeries where they may act as bone-graft substitutes.
- Minimally invasive surgery approaches hold the potential for improved early outcomes, but techniques and instruments are still evolving and studies to date have not unequivocally proven their worth over traditional approaches.
- Computer navigation has the potential to improve outcomes in minimally invasive surgery approaches and is also useful as a research tool. As with minimally invasive surgery, this is also an evolving field where debate is ongoing over issues such as the accuracy of image-based versus image-less systems, tracking and calibration systems and the length of the learning curve involved.
- Ethical issues and dilemmas have also been raised regarding the implementation of new and costly technologies and when it is appropriate to introduce these technologies from the research bench to the bedside.

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