Total Hip Replacement: The Current Perspective After 37 Years

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The first hip replacements of the modern era were performed by Sir John Charnley in 1959, using polytetrafluoroethylene for the acetabulum and polymethylmethacrylate cement to secure the stainless steel femoral component. These initial operations were not a success due to excessive wear of the PTFE bearing surface. The operation was not acknowledged to be the success it is today until 1962 when Charnley switched to using high-density polyethylene for the acetabular component and the "low-friction arthroplasty" was introduced.[1] This prosthesis has remained the "gold standard" until the present day with relatively few changes to the original concept, and with considerable success with published results in excess of 20 years.[2]

However, over the last 30 years, a number of problems have been identified, the most important of which is implant loosening and resultant failure of the prosthesis. The quest to reduce the incidence of loosening has led to continuing evolution of cemented hip replacements and cementing technique and, in the early 1980s, to the development of uncemented fixation to deal with what was felt to be loosening as a result of "cement disease"[3] and high failure rates in younger patients.[4,5] A number of long-term follow-up studies are now becoming available, and with large scale audits of hip replacement practice such as the Swedish prospective study of 92,675 cases,[6] the information is becoming available to identify which procedures are successful on a long-term basis.

In both cemented and uncemented systems, long-term fixation of the components can be achieved with modern techniques, but two main problems remain: wear of the bearing surface leading to particulate debris, and secondary osteolysis which develops as a response to the biological effects of these particles. Both cemented and uncemented systems continue to evolve and improve and there have been considerable advances over the last 37 years. As yet the perfect hip arthroplasty has not been achieved (i.e., an implant which is totally biocompatible and will outlast the patient without need for revision and with a return to normal function with abolition of pain). The current state of development of hip replacements is as follows.

CEMENTED FEMORAL COMPONENTS

Since its inception in the early 1960s, there has been a continued evolution in the

design and application of cemented femoral components. Cementing techniques have improved from the original "first generation" methods which were characterized by finger packing, the absence of an intramedullary cement plug, and with no pressurization of the cement through the "second generation techniques" characterized by an intramedullary plug, cleaning and drying of the femoral canal, and retrograde introduction of the cement by use of a gun. This change occurred in the mid to late 1970s and was associated with improved stem design, with a widened medial edge and broad radius geometries to reduce the probability of micro-fractures occurring in the cement in compression, and with the use of the so-called superalloys to reduce the incidence of stem fracture. A number of clinical studies showed improved longevity as a result of these changes,[7] with femoral loosening rates dropping to as low as 2 to 3%, in comparison to radiographic loosening as high as 30 to 40% in earlier studies.[8,9] This decrease in the incidence of femoral component loosening was also apparent in younger patients, for whom the results of early studies had been disappointing,[10] challenging the presumed unsuitability of these techniques in the younger (less than 50) age group. Although stem geometry and cement formulation have remained fairly static over the last decade, there have been further advances in cementing technique and in the understanding of the interfaces between cement–bone and cement–stem leading to the so-called third generation cementing techniques. Mixing the cement in a centrifuge, cooling, and vacuum mixing all decrease the viscosity of the cement and increase its in vitro strength by up to 5 times.[11] Pressurization of the cement after insertion enhances the bone cement interface by increasing the mechanical interlock as a result of increased cement penetration into the cancellous bone. Pressurization of the cement can also be enhanced by the geometry of the femoral component—flanges and a tapered configuration both increasing the radial displacement of the cement as the stem is introduced. The increasingly widespread use of PMMA "cementralizers" on the tip of the stem reduces the incidence of stems "bottoming out," a known predisposing factor to early loosening[12,13] and decreases abnormally high tensile stresses that can occur in assymetrically thinned areas of cement around the tip of a misplaced prosthesis.

Two factors which have remained contentious are the enhancement of the cement–stem interface either by precoating the stem with PMMA[14] or by roughening the surface of the stem in selected areas, and the use of a collar. The use of a collar has been advocated primarily to increase load transfer to the proximal medial cortex in an attempt to avoid stress shielding and subsequent adaptive re-modeling and bone loss and also to reduce the strain on the proximal medial cement mantle. Doubts have been raised as to the possibility of obtaining accurate medial neck–collar contact and maintaining this contact even if it is achieved.[15,16] More recent studies have shown that using contemporary instrumentation, contact can be achieved in 91%, and maintained at an average of 5.8 years in 88%.[17]

Two opposing hypotheses have developed with regards to the need to enhance the cement bone interface: that of Fowler et al.[18] who advocate a collarless polished taper, and Harris[14] who has advocated a stem precoated with PMMA and a collar. Clinical follow up of the Exeter total hip replacement[18] at 17 years revealed the phenomenon of distal movement of the stem within the mantle of cement, without disruption of the cement bone interface. Examination of a number of relevant cement mantles and laboratory experiments suggested to the authors that this stem movement is a result of creep of the cement, and represents engagement of the taper of the stem, which becomes progressively tighter and more stable as it engages, which assists in the transmission of load to the proximal femur, reducing stress shielding to a minimum. A combination of the low frictional coefficient of the polished surface and the presence of a thin < 100 micron fibrous layer at the stem–cement interface lead to a relative increase in the compressive load, and a decrease in the shear component of the load, the situation in which bone–cement is at its strongest. The Exeter hypothesis postulates that this potential for movement is essential to protect the bone–cement interface and that maintaining the cement in compression reduces the incidence of cement fracture and debris formation. A change to a matte surface in the late 1970s led to a high incidence of early loosening and was rapidly changed back to the original polished finish supporting the hypothesis.[19]

Harris argues that it is advantageous to maintain a stable, strong cement–stem bond and that this should not be associated with increased strain on the cement–bone interface. This is supported by the authors histological examination of postmortem specimens of well-fixed cemented femoral components with intact, extensive osseointegration at the cement bone interface and with bonded cement–metal interfaces.[20] It has been postulated that loosening of the femoral component is predominantly initiated by debonding at the cement–stem interface[21] and that once debonding begins it is a progressive process. Such debonding should in theory be prevented by precoating, but opinion following finite element analyses varies as some authors have suggested that partial debonding decreases cement stresses,[15] while others suggest that partial debonding may increase stresses.[22]

The theoretical evidence supporting the use of precoating and collars is impressive. However, there is not as yet the long-term clinical experience available for these methods of fixation and only time will tell what is the right approach to femoral fixation. The clinical results with second-generation cementing techniques are now so good, including in younger patients,[10,23] that acetabular component fixation is now perceived as the weak link.

UNCEMENTED FEMORAL COMPONENTS

Uncemented femoral fixation was advocated in total hip replacements in the early 1980s to counter the growing concern of femoral loosening and peri-prosthetic osteolysis. A number of materials have been used in uncemented femoral stem design, including cobalt chrome alloy, titanium alloy, stainless steel, and a small number of low elastic modulus composite designs. Of these, only the first two have proven successful and are still in regular use. There are a number of biomechanical reasons for which titanium would appear to be the better choice. The primary biomechanical advantage of titanium over cobalt chrome is its lower elastic modulus, which should result in increased load transfer, and less stress shielding to the proximal femur; this advantage is, however, progressively lost, as thicker stems are needed in larger femurs. Titanium is also known to exhibit superior bone ingrowth when compared to cobalt chrome and is known to be biocompatible and non-toxic in the physiological environment. Despite these theoretical advantages, titanium stems have not yet shown such an advantage in clinical studies and long-term results are not

yet available. The longest available follow-up to date is with straight stem, extensively porous coated cobalt chrome prosthesis (Anatomic Medullary Locking, DePuy, USA). Sotereanos et al.[24] described two series of patients with this prosthesis; 122 patients were available for follow-up who were operated on prior to 1982 when only a single stem size was available. Of these patients at an average follow-up of 10.2 years, only five stems required revision with a calculated survival probability of 95.4%. Of the second series of 227 patients in which multiple stem sizes were available, 171 were available for follow-up at an average of 8.3 years. Only one stem required revision, with a predicted survivorship of 99.3% at 9 years, although three patients developed extensive osteolytic lesions in Gruen[25] femoral zone 1 (greater trochanter) requiring an "interval" procedure of acetabular polyethylene exchange and allografting of the femoral and associated acetabular osteolytic lesions. In both series there were no osteolytic lesions below the level of the lesser trochanter and no unrevised implants which were considered potential failures as a result of stress shielding. These results are compatible with the evidence of a number of authors who have stressed the importance of proximal circumferential porous coating[26,27] which appears to limit the "effective joint space"[28] and restrict debris migration and subsequent polyethylene granulomas and osteolytic lesions. Less extensively porous coated cobalt chrome implants have not been as successful with high incidences of osteolysis in all seven Gruen zones.[29] A similar effect has been noticed with titanium femoral implants, and early less successful designs have largely been replaced by more extensively coated implants. At this stage it is not possible to apply an extensive porous coat to the entire length of a titanium stem without risk of stem fracture. Plasma spraying and grit blasting have been used to surface finish titanium stems, which rely on the metal's intrinsic ability to support osseointegration. These types of prostheses, however, rely on initial press fit stability which requires aggressive femoral canal fitting, which increases the risk of femoral fracture.

A promising area of development in the coating of titanium femoral stems is the use of hydroxyapatite (HCA). Initial reports on the use of HCA coatings reported instability of the coatings with increased debris formation and third body wear.[30] More advanced manufacturing techniques have attempted to abolish this phenomenon, and review of a proximally HCA-coated femoral stem[31] at an average of 6.2 years has revealed 100% survivability of the implant with very low incidence of thigh pain, which has been a problem with a number of uncemented stems since their inception. At this early stage the bone remodeling characteristics around this prosthesis are more favorable than reported with extensively porous coated cobalt chrome series and with a low incidence of osteolytic lesions, all confined to the calcar resection level. The development of these implants is at an early stage and only time will tell if in the long term they are more successful than the alternatives. Stress shielding and secondary bone loss in the proximal femur may become a greater concern as longer follow-up is achieved, as may the difficulty of extracting a successfully osseointegrated extensively coated prosthesis if revision is required.

CEMENTED ACETABULAR COMPONENTS

There have been few significant alterations in the design and application of cemented acetabular components since their initial introduction by Charnley. Experience with his initial series has questioned the wisdom of reaming away the hard subchondral bone which is now preserved whenever possible. There have been improvements in both the formulation and manufacture of the cup to improve the bearing surface, and in some cases flanges have been added to increase cement pressurization as the cup is introduced. Finite element analyses have suggested that metal backing of polyethylene cemented components should reduce the strain at the cement–bone and cement–prosthesis interfaces.[32] This theoretical advantage has not been demonstrated by clinical studies.[33] The dramatic improvement in longevity seen in femoral components following the introduction of second generation cementing techniques was not apparent on the acetabular side, and acetabular loosening is now the major concern with all cemented systems. Numerous reports have shown radiological loosening of Charnley acetabular components at 10 to 15 years at between 8.4%–25%,[34-37] and as many as 54% at greater than 20 years.[38]

Retrieval of acetabular components has indicated that osseointegration does not occur at the bone–cement interface to the same degree as as it does on the femoral side and that an intervening layer of fibrous tissue is present.[39,40] The dominant mechanism of late loosening of these components is macrophage-induced bone resorption at the bone–cement interface as a result of particulate polyethylene debris.[41]

UNCEMENTED ACETABULAR COMPONENTS

Uncemented acetabular fixation was developed as a response to the same perceived problems as on the femoral side. Uncemented acetabular components have developed with two main types of initial fixation: threaded, or hemispherical press fit with or without screw augmentation. Both types then require secondary osseointegration with a similar variety of porous coatings and surface preparations as the femoral components. With one exception,[42] clinical results of cups with peripheral threads or screw-in type cups have been disappointing.[43] The early results of hemispherical porous ingrowth type cups have been encouraging: at a minimum follow-up of 5 years, there had been no revisions for asymptomatic loosening with the Harris–Galante titanium fiber mesh component[44] (Zimmer, USA), no apparent migration, and only two cases with minimal osteolysis around screws. The incidence of osteolysis around hemispherical porous coated acetabular components appears very implant-dependent. In a series utilizing the Porous Coated Anatomic (Howmedica, USA), 4.5% of acetabular components required revision as a result of pelvic osteolysis at an average duration of only 7.5 years,[45] and with the same prosthesis at 6 years, 10 out of 116 patients showed pelvic osteolysis with lesions ranging from 1 to 7.5 cm in diameter.[29] A number of unrelated design features may be related to this marked difference in occurrence, such as the thickness of polyethylene used, femoral head size, conformity of the polyethylene liner within the metal shell, size and number of screw holes, and the presence or absence of polyethylene pegs. The pattern of osteolysis around uncemented acetabular components differs from that seen around cemented components: it is often localized and expansile, producing more bone loss, but may not always be associated with loosening of the cup.[46]

SUMMARY

In both cemented and uncemented prostheses, the predominant long-term problem is periprosthetic osteolysis, and

the resultant bone loss and loosening of the implant. Histological analysis has revealed that this macrophage-induced bone resorption is a reaction to polyethylene particulate debris. Polyethylene is used as the acetabular-bearing component in the vast majority of total hip replacements, so naturally attention has recently been focused on reducing polyethylene wear and also to the possibility of removing polyethylene from the articulation altogether. With the original concept of the low-friction arthroplasty, Charnley recognized that polyethylene wear would be crucial if the operation was to be a long-term success, and addressed the problem in a number of ways, including the utilization of a highly polished femoral head of only 22 mm diameter with the aim of reducing frictional torque and therefore also the strains on the bone–cement and cement–prosthesis interfaces. This small head diameter also allows for a thicker polyethylene cup which has a similar beneficial effect on stress transfer. The theoretical downside of this small head diameter is the potential for higher contact stresses and a higher dislocation rate. To this date, however, the long-term polyethylene wear rates of the Charnley prosthesis have not been significantly improved upon by any metal–polyethylene articulation. There is considerable optimism that alumina ceramic modular heads will produce less long-term polyethylene wear, and now that initial manufacturing problems have been overcome and fears of impact failure have been dismissed, the potential of this material may be realized as the results of long-term clinical studies become available. Another field of development is the renewed interest in metal-on-metal articulations, which were first used in the 1960s[47] in the McKee–Farrar total hip replacement. This prosthesis was not a long-term clinical success but was implanted in large numbers, a small number of which survived for more than 20 years and in which, when revised, very little wear was apparent, and with no abnormal staining of the capsular tissues. With modern designs and fixation methods, and more advanced manufacturing techniques, a number of these prostheses are already in clinical use. If clinical data in long-term studies can match laboratory data with regards to debris formation and friction moment, these articulations could provide a solution to the problem of polyethylene debris which has threatened the longevity of total hip replacements to date. **STI**

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