

## The operation of the century: total hip replacement

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In the 1960s, total hip replacement revolutionised management of elderly patients crippled with arthritis, with very good long-term results. Today, young patients present for hip-replacement surgery hoping to restore their quality of life, which typically includes physically demanding activities. Advances in bioengineering technology have driven development of hip prostheses. Both cemented and uncemented hips can provide durable fixation. Better materials and design have allowed use of large-bore bearings, which provide an increased range of motion with enhanced stability and very low wear. Minimally invasive surgery limits soft-tissue damage and facilitates accelerated discharge and rehabilitation. Short-term objectives must not compromise long-term performance. Computer-assisted surgery will contribute to reproducible and accurate placement of implants. Universal economic constraints in healthcare services dictate that further developments in total hip replacement will be governed by their cost-effectiveness.

Palaeopathologists have diagnosed osteoarthritis of the hip in ancient skeletons,<sup>1</sup> and prevalence and distribution of the disease then seems no different from today.<sup>2</sup> However, little more than 100 years ago, the first attempt was made to treat hip arthritis surgically. Interpositional arthroplasty, offered in the late 19th and early 20th centuries, entailed replacing various tissues—including fascia lata, skin, and even the submucosa of pig's bladder—between the articulating surfaces of the hip. Interposition of a vitallium cup, which covered the reshaped femoral head, by Smith-Peterson in 1938 heralded a new era of arthroplasty.<sup>3</sup>

Wiles developed the first prosthetic total hip replacement in 1938,<sup>4</sup> and this implant is regarded as the precedent of the modern genre. Subsequent attempts at reconstruction of destroyed arthritic joints are testimony to the ingenuity of surgeons of that time. These early endeavours were largely betrayed by poor design, inferior materials, and mechanical failure. Charnley revolutionised management of the arthritic hip with the introduction of low friction arthroplasty (figure 1).<sup>5</sup> He made three major contributions to the evolution of total hip replacement: 1) the idea of low friction torque arthroplasty; 2) use of acrylic cement to fix components to living bone; and 3) introduction of high-density polyethylene as a bearing material. Reviewing first-generation results of Charnley's low friction arthroplasty, Berry and colleagues<sup>6</sup> and Callaghan and co-workers<sup>7</sup> reported 81% and 77% survivorship, respectively, at 25-year follow-up, with revision of any component as the endpoint. Similar data have been reported by other researchers.<sup>8–10</sup> These findings lend support to Coventry's observation in 1991 that "Total hip arthroplasty, indeed, might be the orthopaedic operation of the century".<sup>11</sup>

Fender and colleagues reviewed 5-year outcomes of 1198 patients who underwent Charnley's low friction arthroplasty across one health region in England.<sup>12</sup> They recorded a failure rate of nearly 9% and noted that although this proportion was higher than those published from specialist centres, it was probably more representative of the norm. The surgical technique in this series did not adhere uniformly to contemporary cementation philosophy. Failure mechanisms of early total hip replacement included

fracture of the implant,<sup>13</sup> aseptic loosening as a result of mechanical failure of the fixation interface,<sup>14</sup> infection,<sup>15</sup> polyethylene wear,<sup>16</sup> and dislocation.<sup>17</sup> Furthermore, high failure rates were reported in young patients.<sup>18–20</sup>

Indications for total hip replacement were initially largely restricted to either elderly and infirm people or individuals with locomotor limitations associated with other comorbidities. However, today, an unacceptable compromise in quality of life constitutes a valid indication for total hip replacement, and patients seek so-called high-performance hips to deliver their expectations and aspirations. Developments in total hip arthroplasty have been directed at reduction of the rate of failure while accommodating the high-activity profile and increased longevity of the modern patient. Components must, therefore, provide durable fixation in the face of high stresses, whereas bearing surfaces need to be resilient and show low wear. This Review describes developments of total hip arthroplasty designed to provide a stable and durable implant tailored to meet specific requirements of the individual patient.

### Cemented total hip replacement

Glück, a German surgeon, was the first researcher to use cement "for a better fixation" of both components of an ivory total knee replacement in 1891.<sup>21</sup> However, Charnley introduced and popularised use of polymethyl methacrylate bone cement for fixation of total hip prostheses in the late 1950s.<sup>22</sup> Although cemented fixation includes both

#### Search strategy and selection criteria

We searched PubMed and Medline from 1966 to April, 2006, with the terms: "total hip arthroplasty", "cemented femoral stems OR acetabular cups", "cementless femoral stems OR acetabular cups", "bearing surfaces in hip replacement", "metal-on-metal", "ceramic bearings in hip replacement", "outcomes OR survivorship in hip replacement", and "minimally invasive hip surgery". Websites of arthroplasty hip registries and the National Institute for Clinical Excellence were searched, and, when possible, results were included from randomised trials.

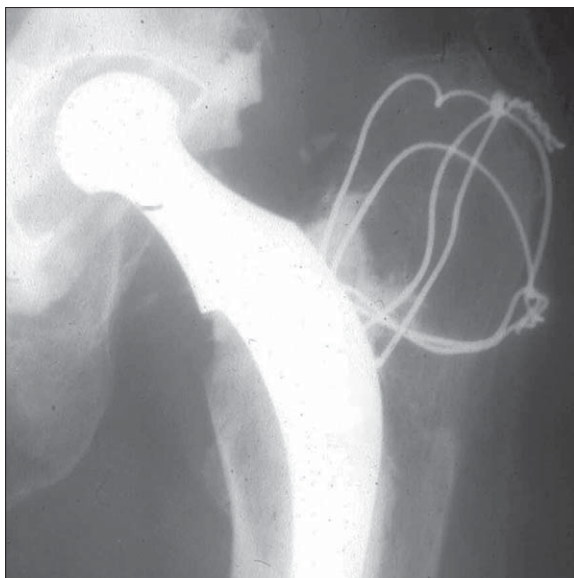


Figure 1: Radiograph of 26-year follow-up of first-generation Charnley low friction arthroplasty

bone-cement and cement-implant interfaces, the bone-cement surface is the one that provides the foundation for durable fixation. Cemented total hip replacement is highly technique-dependent because the surgeon manufactures the bone-cement-implant composite at the time of surgery.

Although the chemical composition of bone cement has essentially remained the same over the years, the cementation technique has changed greatly. Early methods entailed limited, if any, preparation of the bone bed; cement was introduced antegrade; and little attempt was made at pressurisation beyond finger-packing. This technique resulted in poor penetration into cancellous bone, inadequate cement mantles, and lamination of the cement. Cement is a grout not a glue: fixation is achieved by mechanical interlock rather than adhesion. Two groups of researchers<sup>23,24</sup> have shown that increased pressurisation of cement enhanced penetration into bone interstices, which was associated with raised tensile and shear strengths at the bone-cement interface. Furthermore, in two separate reports, workers noted that cleaning the endosteal surface contributed to augmented cement intrusion into bone and enhanced the interface shear strength.<sup>25,26</sup> Contemporary cementation techniques include cleaning of the endosteal bone with pulsed lavage, retrograde insertion, and sustained pressurisation to optimise micro-interlock. Proximal and distal centralisers facilitate reproducible creation of a complete, uniform, cement mantle.<sup>27</sup> The benefits of contemporary cementing techniques have been shown in the Swedish hip register,<sup>28</sup> and very good mid-to-long-term results have been published.<sup>29</sup>

Design of the cemented stem embraces two broad ideas: a taper-slip or force-closed design, and a composite-beam or shape-closed design. The taper slip is a highly polished tapered stem designed to settle within the cement mantle

and re-engage the taper. Optimisation of load distribution to surrounding bone and cement is achieved by conversion of shear stresses to radial-hoop stresses. By contrast, fixation of the composite beam relies on the shape of the implant and the composite fixation of stem to cement and cement to bone. In the Swedish hip register, 98% survivorship was reported for both the Spectron (Smith & Nephew, Memphis, TN, USA)—a shape-closed design—and the Exeter (Stryker, Newbury, UK)—a taper-slip design—at 9 and 7 years, respectively.<sup>19</sup> Williams and colleagues reported 100% survivorship of the Exeter stem at 10-year follow-up, with aseptic loosening as the endpoint.<sup>30</sup> After noting that good results over a lengthy follow-up period were needed to identify long-term complications, Wroblewski introduced a third taper from lateral to medial in the C-stem (DePuy, Leeds, UK) believing that it would improve loading and thus bone preservation in the calcar over time (figure 2). He reported 100% survivorship of the C-stem at 7-year follow-up, with aseptic loosening as the endpoint.<sup>31</sup>

The above two fixation ideas demand an adequate and complete cement mantle. In France, the notion evolved of inserting the largest stem possible, by which the rectangular cross-section would provide rotational stability even in the absence of cement. This strategy resulted in the so-called French paradox, whereby good results were reported with oversized stems when the cement mantle was excessively thin or deficient.<sup>32</sup>

Charnley was concerned at the fairly high rate of fracture of his first-generation stems. He recognised that this risk was the result of cantilever bending of a distally well-fixed stem.<sup>33</sup> Changing the cross-sectional geometry and



Figure 2: Radiograph of highly polished triple-tapered cemented C-stem and uncemented cup

Note the enhanced cementation of the stem compared with figure 1.

dimensions not only produced a much stiffer stem but also changed the design from a taper slip to a composite beam. This alteration introduced different failure mechanisms.<sup>34</sup> Although the frequency of stem fracture was reduced, aseptic loosening rose, with an overall increase in rate of failure.

Ideas should not be exported from one design to another. In the late 1970s, an Exeter stem was produced with a matt surface. This device had a threefold higher failure rate (10% at 8 years) than its otherwise identical highly polished predecessor.<sup>35</sup> Similarly, the design of the Capital Hip (3M Healthcare, Loughborough, UK) was based on the Charnley range but the prescribed surgical technique produced a thin cement mantle. The stainless steel monobloc component worked reasonably well but the modular implant made of titanium was associated with early osteolysis and a high frequency of loosening.<sup>36</sup> Even a small change in design can have a substantial effect on long-term outcome.

Improvement in cemented fixation of the acetabular component also entails cleaning and drying of the reamed acetabulum and sustained pressurisation of cement. The design of the polyethylene cemented cup has changed little over the decades, although addition of a flange has enhanced pressurisation. Havelin and colleagues,<sup>37</sup> analysing the Norwegian arthroplasty register, noted that hydroxyapatite-coated uncemented cups did not perform better than the Charnley cup. Their data should be interpreted with some caution because quality of fixation of the different cementless cups varied greatly.

Encouraging long-term results of Charnley's low friction arthroplasty have been reported.<sup>67</sup> Refinements in stem design that exploit the visco-elastic properties of cement and enhanced cementation techniques have delivered good mid-term results with modern implants. Long-term follow-up of the Exeter device<sup>38</sup> suggests that there is no reason why results should not be sustained over time. Recognising the bone-preserving potential of contemporary cemented tapered stems, Spitzer noted that "Cement should not be relegated as an inferior fixation option, but rather should be the fixation of choice in most patients undergoing total hip arthroplasty".<sup>39</sup>

### Uncemented total hip replacement

Early failure of cemented stems implanted by first-generation cementation techniques was frequent. These failures were associated with localised areas of bone destruction and resorption (osteolysis). Their cause was initially believed to be infection<sup>40</sup> but was subsequently attributed to a local inflammatory response initiated by cement particles. In the 1970s, histological examination of tissue taken from these localised areas of osteolysis showed the presence of polymethyl methacrylate debris,<sup>41</sup> and as a result, researchers assumed that premature loosening of cemented components was related to so-called cement disease.<sup>42-44</sup> Because of this occurrence, several investigators thought that the future of total hip replacement should be

directed towards development of prostheses that could be implanted without use of cement on either the femoral or the acetabular side. Thus, by removing the apparent cause of cement disease (polymethyl methacrylate debris), the primary mechanism of failure of cemented implants might be eliminated.

Cementless femoral and acetabular components were designed to provide adequate initial stability and to encourage bone to osseointegrate onto or into the implant. Stems had to be made with either a porous coating of some description or, at the very least, a roughened surface that would allow intimate bony apposition to anchor the implant. Once the implant was biologically stabilised in bone, which could take several months, the femoral component would allow normal transmission of biomechanical forces across the joint.

Early designs of femoral porous-coated implants were cylindrical, with extensive coating of the length of the implant. As a result, good diaphyseal bone ingrowth took place, but unfortunately many of these designs were associated with a high rate of cortical atrophy, proximal stress-shielding, and bone loss. Furthermore, patients sometimes complained of thigh pain, presumably due to elastic mismatch between the rigid stem and the biologically flexible femur.<sup>45,46</sup>

In an attempt to provide enhanced physiological proximal loading of the femur, cementless femoral components were designed that were still cylindrical in shape distally but had a porous ingrowth surface located proximally, in the metaphyseal region. Researchers hoped that biological ingrowth in this area would enhance physiological loading and protect against proximal stress, shielding osteopenia of the femur.<sup>47</sup> Some of the early stems did not have circumferential porous coating but rather had patches of this coating located anteriorly and posteriorly as well as medially or laterally. These designs, however, had a high frequency of failure, with large amounts of osteolysis recorded distally. The cause of this osteolysis was believed to be polyethylene particles, which gained access to the distal femur through channels between the areas of porous coating.<sup>48</sup> This theory led to development of implants with circumferential proximal porous coating in an attempt to eliminate access channels for particulate debris.

In addition to type and location of surface texturing, femoral components vary in shape and by material and mechanical properties. All uncemented femoral stem designs rely on metaphyseal fixation, metaphyseal-diaphyseal junction fixation, diaphyseal fixation, or a combination of the three. Although many stem designs are currently on the market, all fall into three broad designs: anatomic, tapered, or cylindrical.

Anatomic stems, as the name implies, incorporate an anteroposterior curve to match the natural bow of the patient's femur. These devices were designed around the idea that a curved stem in a curved bone would provide good initial stability and thus subsequently increase bony

ingrowth. Researchers hoped that the anatomic design would allow for enhanced physiological loading of the femur and thus reduce stress-shielding and distal thigh pain. Regrettably, however, this outcome was not the case and, indeed, data for most published studies on anatomically shaped stems indicate a higher frequency of thigh pain than with other traditional designs (tapered or cylindrical).<sup>49,50</sup>

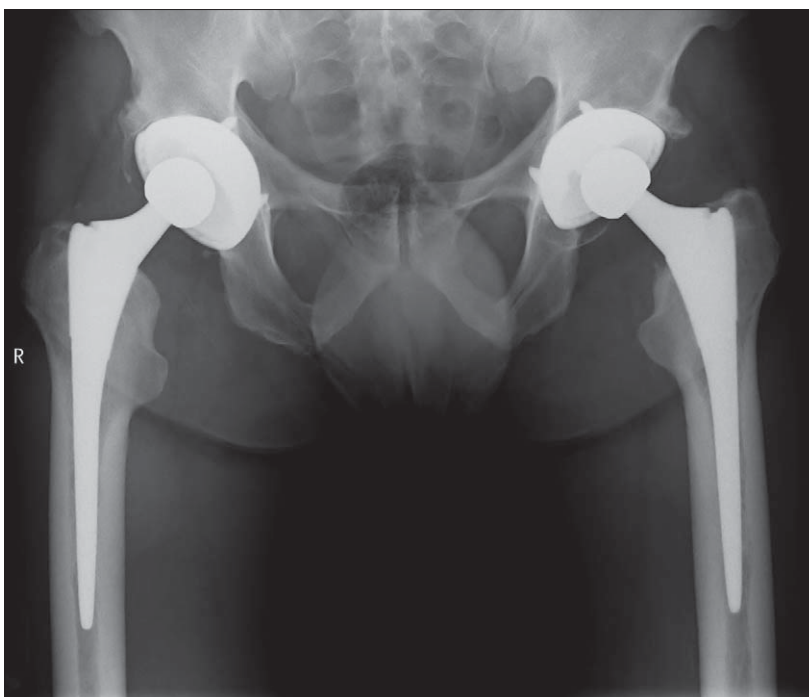
Tapered stems use proximal cancellous bony ingrowth and three-point stem fixation to obtain immediate stability. Clinical results of straight tapered stems with at least 10-year follow-up have been good, with stem survivorship reported between 92% and 100% (figure 3).<sup>51–53</sup> Thigh pain, although occasionally encountered with tapered designs, was largely eliminated when compared with anatomic or cylindrical stems.

Cylindrical stems need distal cortical support to gain immediate stabilisation. Moreover, distal fixation and osseointegration allow for a greater lever arm to resist torsional forces compared with proximally coated stems. To achieve distal fixation, the prosthesis must be canal-filling, generally needing an implant of large diameter. Stem stiffness depends on the elastic modulus of the material and is proportional to the fourth power of the diameter. Thus, increasing the stem diameter boosts stem stiffness, a factor that has been linked to distal thigh pain and proximal stress-shielding. The frequency of thigh pain has been reported between 1.9% and 40%. The cause of this pain is related to large stem size, distal porous coating, and material composition.<sup>45,46</sup> In a further attempt to lessen stem stiffness, implants have been designed with coronal slots within the distal third of the stem and longitudinal grooves that can enhance stem strength without increasing the diameter.

Although most fully porous-coated tapered stems are made of cobalt chrome, no difference has been recorded in survivorship of stems made of titanium. Titanium has a lower modulus of elasticity—closer to that of host bone—and is more biocompatible than cobalt chrome. On the other hand, titanium is notch-sensitive, which predisposes it to cracks if the stem is not well supported.

Cementless acetabular cups were introduced to alleviate the difficulty with fixation failure of cemented polyethylene sockets. At 12–15 years, Charnley reported continuous radiolucent demarcation around cemented cups in 14% of patients.<sup>40</sup> The failure rate was greatest in young patients, and Barrack and colleagues reported 44% loosening of cemented sockets at 12 years in individuals younger than 50 years.<sup>54</sup> Cementless acetabular cups are hemispherical in shape and most are entirely porous-coated for bone ingrowth. Initial stability and fixation can be achieved by press-fit of the component; additional attachment can be provided by pegs, spikes, screws, or a threaded-cup design. Several research groups have noted early failure of the threaded-cup design.<sup>55,56</sup>

Press-fit components avoid the need for screw placement, which carries the added risks of neurovascular



**Figure 3: Radiograph of bilateral uncemented tapered stems at 10-year follow up**  
These stems are designed to obtain fixation in the metaphysis to reduce the frequency of thigh pain and of stress-protection osteopenia.

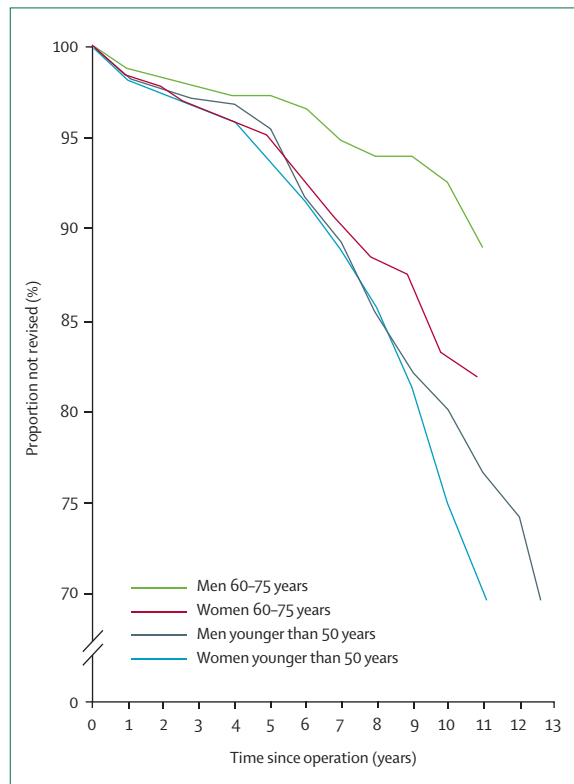
injury and fretting wear between screw and shell. Press-fit devices have shown good intermediate results.<sup>57</sup> Components inserted with additional screw fixation have 96% survivorship at 10 years.<sup>58</sup>

Failures of cementless cups include accelerated polyethylene wear, malfunction of the locking mechanism of the polyethylene liner in the metal-backed shell,<sup>59–62</sup> and extensive periacetabular osteolysis.<sup>63</sup> Screw holes in the shell enable debris to access the periacetabular cancellous bone, a further extension of the effective joint space. Modifications to acetabular shells with polished internal surfaces and better locking mechanisms should reduce these complications. Many uncemented components have predominantly fibrous tissue at the fixation interface instead of bony ingrowth.<sup>64</sup> Hydroxyapatite has been used to enhance bone ingrowth and stimulate bony gap closure.<sup>65–67</sup>

Long-term results for uncemented total hip arthroplasty are poor compared with its cemented counterpart.<sup>68</sup> Medium-term data for patients younger than 50 years are inferior to those for people older than 60 years at time of surgery (figure 4). Data for uncemented stems are good.<sup>51,53,69–71</sup> Acetabular component survival is poor: a high proportion of failures is due to polyethylene wear and osteolysis (figure 5).<sup>70,71</sup>

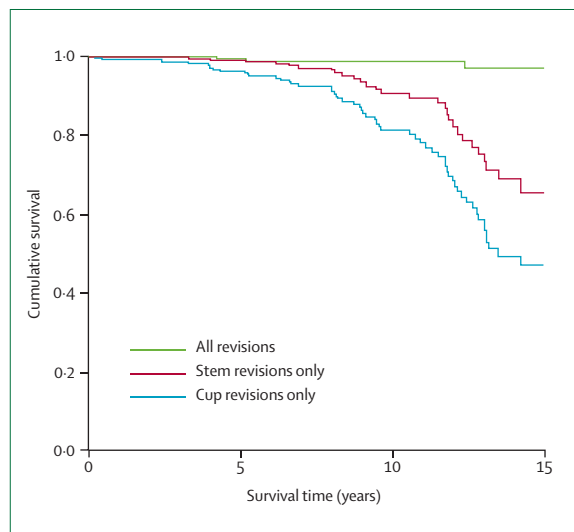
Implant stability and fixation are crucial for durability. Research is currently focused on creation of an osteogenic stimulus to enhance bone ongrowth or heal bony defects.<sup>72–74</sup> Work in nanotechnology to investigate the effectiveness of

incorporating biologically active proteins onto implants to enhance fixation is in its infancy, but if successful it could provide the implant coating of the future.



**Figure 4:** Survival of uncemented implants in patients younger than 50 years and older than 60 years based on data from the Swedish National Hip Arthroplasty Register, 2004

All diagnoses and all reasons for revision are included. Figure reprinted from reference 68 with permission of the Swedish National Hip Arthroplasty Register.



**Figure 5:** Survival of uncemented implants in patients younger than 50 years, using revision as an endpoint

Figure reprinted from reference 72 with permission of Lippincott, Williams, and Wilkins.

### Bearing surface

The issue of osteolysis has not been resolved by implantation of uncemented components. Lytic defects have been reported with both stable and loose uncemented prostheses.<sup>75</sup> In the late 1970s, several researchers<sup>76,77</sup> made important initial contributions to knowledge about the role of particles generated by joint prostheses in the pathogenesis of osteolysis and aseptic loosening. Further histological assessment of tissue from these defects indicated that osteolysis was related to the macrophage response to polyethylene debris.<sup>48,78–80</sup> Fragments from polyethylene wear, rather than cement particles, were then recognised as the major limitation to conventional total hip arthroplasty.

Polyethylene wear and debris formation result in synovitis, joint instability, osteolysis, and prosthesis loosening. Alternative bearing surfaces—such as metal on cross-linked polyethylene and hard-on-hard bearings (metal-on-metal or ceramic-on-ceramic)—have been assessed in an attempt to reduce wear and improve longevity of total hip arthroplasty procedures, especially in young, high-demand, active patients. The introduction of cross-linking of ultrahigh-molecular-weight polyethylene was intended to address the issue of wear and osteolysis by reducing the number of submicron particles generated. Gamma irradiation of polyethylene causes cross-linking, which greatly improves wear resistance compared with conventional polyethylene.<sup>81,82</sup> Short-term clinical results for cross-linked ultrahigh-molecular-weight polyethylene suggest a reduction in wear versus conventional polyethylene.<sup>83</sup>

Metal-on-metal bearing surfaces were first used widely in the 1960s.<sup>84–86</sup> Poor materials and designs with equatorial (edge of head diameter) bearing combined with inferior fixation condemned these prostheses to early failure. However, long-term follow-up of implants with polar (central head) bearing showed good survival and little wear without the difficulties associated with polyethylene-induced osteolysis.<sup>87</sup> This finding led to a resurgence of interest in the in-vitro and in-vivo wear properties of metal-on-metal articulations.<sup>88–90</sup> Metal bearing surfaces have low wear rates—in the region of 0.004 mm per year compared with 0.1 mm per year for polyethylene. Metal is not brittle, unlike ceramic, and components therefore do not have to be as thick as ceramic ones do. Thus, for a given acetabular shell size, a large head diameter can be used (figure 6), which provides enhanced joint stability and a large range of movement before the neck impinges on the socket. It also produces a fast sliding speed of the bearing, contributing to better lubrication. Metal-on-metal bearings are self-polishing, allowing for self-healing of surface scratches. Although these bearings have the potential for low wear rates, there is concern about generation of metal ions (both cobalt and chromium), which are detectable systemically.<sup>91–93</sup> Although raised amounts of cobalt and chromium ions can be recorded in blood and urine, no long-term adverse biological effects have yet been reported.<sup>94</sup>

Alumina ceramics were introduced in the 1970s. They have a low coefficient of friction, superior wear rates,<sup>95</sup> are scratch-resistant, have no potential for ion release, and the particulate debris is not very biologically active.<sup>96</sup> However, ceramics do have the potential to fracture because of their brittle nature.<sup>97,98</sup> Good short-term results have been reported<sup>99</sup> for both alumina-on-alumina and alumina-on-polyethylene couplings.

Oxidised zirconium metal (Oxinium, Smith & Nephew) has been developed, which has the wear resistance of ceramic without the brittle fracture risk.<sup>100,101</sup> Findings of clinical studies have yet to provide in-vivo confirmation of the laboratory wear rates achieved.

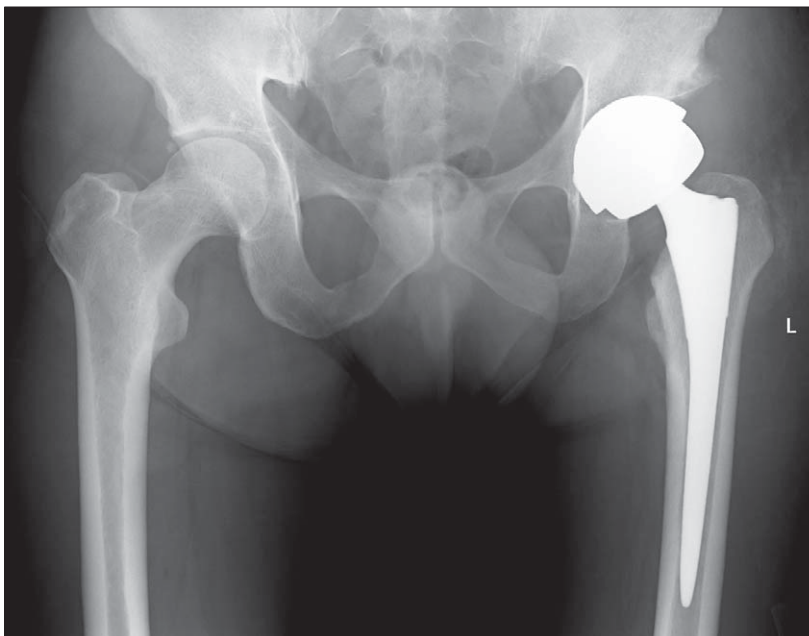
### Bone-conserving femoral implants

Arthritis of the hip mainly affects articular surfaces of the joint and subchondral bone. Intuitively, resurfacing of the joint is the logical conservative surgical option. Resurfacing prostheses that were popular in the early 1970s had a large diameter head articulating with a cemented polyethylene acetabular component. The polyethylene was very thin, and this aspect—together with the high frictional torque generated by the large diameter head—produced catastrophic wear of the plastic, osteolysis, and implant failure. Early and mid-term failure rates of up to 33% were reported.<sup>102–105</sup>

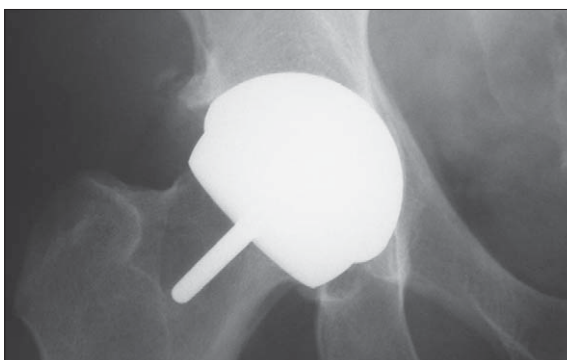
After recognising the possible bone-conserving benefits of resurfacing arthroplasty, researchers looked into reduction of wear generated at the articular couple. Contemporary metal-on-metal bearings produce very low wear and more than 300 000 have been inserted worldwide over the past 10 years. Exploiting this technology, McMinn showed that acceptable mid-term results could be achieved with metal-on-metal resurfacing and hybrid fixation (cementless cup and cemented femur).<sup>106</sup> Treacy and colleagues<sup>107</sup> reported 98% survivorship of the Birmingham device (Midland Medical Technologies, Birmingham, UK) at a minimum of 5 years' follow-up, with revision of either component as the endpoint.

Fracture of the femoral neck remains a major cause for concern. Shimmin and Back<sup>108</sup> recorded a 1.46% rate of neck fracture in 3497 Birmingham hips inserted by 89 surgeons in Australia between 1999 and 2004. Factors predisposing to neck fracture included varus placement of the implant and notching of the femoral neck. Amstutz and co-workers<sup>109</sup> noted a prevalence of femoral neck fracture of 0.83% in 600 metal-on-metal resurfacing arthroplasty procedures undertaken between 1996 and 2003. They identified failure to cover all reamed bone with the femoral component as the most important factor leading to fracture.

Refinement of implant design and tribological work to optimise the articular couple might further improve results of resurfacing arthroplasty (figure 7). Although this technique is a valuable addition to the surgeon's



**Figure 6: Radiograph of metal-on-metal articulation, using a large diameter head**  
The large diameter head provides increased mobility with enhanced stability and good lubrication.



**Figure 7: Contemporary metal-on-metal resurfacing arthroplasty**  
This technique is a conservative option.

repertoire in management of the young active patient with hip disease, early and mid-term results do not justify the unbridled enthusiasm with which the uncritical orthopaedic community has embraced this new technology. Narrowing of the femoral neck can arise, which Beaulé and co-workers<sup>110</sup> believe probably indicates an as yet uncharacterised remodelling process that might place the hip at increased risk of fracture over time. Resurfacing is not suitable for all hips,<sup>111</sup> and indications and limitations need to be recognised to reduce the number of technique-related failures.

A high rate of failure has been reported with primary cemented total hip replacements in young active individuals.<sup>112,113</sup> This finding has led many surgeons to investigate use of cementless fixation in this group of patients. However, fixation or cortical contact of the stem in the diaphysis is associated with distal offloading, which predisposes to stress-shielding and loss of proximal



**Figure 8:** Radiograph showing replacement of the femoral head with a Thrust plate prosthesis

bone stock.<sup>114</sup> Furthermore, ever younger cohorts of patients are presenting for total hip arthroplasty.<sup>115</sup> These individuals are likely to need revision surgery, and the major challenge facing the surgeon will be loss of bone stock. These factors, together with the idea that minimally invasive surgery should spare both bone and soft tissue, have provided impetus for development of conservative hip implants.

Although several different conservative implants are currently available, few clinical results have been published. The Thrust plate prosthesis was first implanted in 1978 and has subsequently evolved through three generations (figure 8).<sup>116</sup> Buergi and colleagues<sup>117</sup> reported the clinical and radiological outcome of 102 conservative total hip replacements in which the third generation of Thrust plate was used. Mean follow-up time was 58 months. Survivorship at 5 years was 98%, with revision for aseptic loosening as the endpoint.

The Mayo conservative hip is a wedge-shaped device that tapers in both the sagittal and coronal planes. It is curved distally to provide a flat surface for contact with the lateral cortex (figure 9). Morrey and co-workers<sup>118</sup> described 162 total hip replacements in which this prosthesis was used, with a mean follow-up of 6·2 years. Survival without mechanical loosening was 98·2% at both 5 and 10 years.



**Figure 9:** Mayo conservative femoral prosthesis  
Note the consolidation of bone around the lower metaphyseal region of the implant. Illustration provided by B Morrey, Mayo Foundation.

### Minimally invasive surgery

There is a current trend towards minimally invasive surgery, either through one mini-incision or with a two-incision technique. The claim is that mini-incision procedures reduce pain, blood loss, rehabilitation time, and hospital stay.<sup>119</sup> Single-incision surgery—using the same surgical approach as conventional procedures but with a skin incision of less than 10 cm—has been approved by the UK's National Institute for Clinical Excellence (NICE)<sup>120</sup> based on data from two randomised controlled trials.<sup>121,122</sup> The two-incision technique is more controversial than single-incision surgery. Proponents claim it reduces soft-tissue trauma.<sup>119,123</sup> Compared with the single-incision procedure, the two-incision technique needs more technical expertise, fluoroscopy in theatre, and is associated with a higher complication rate.<sup>124</sup> NICE concluded that there was insufficient evidence for the two-incision procedure to be used without special arrangements.<sup>125</sup>

Minimally invasive techniques reduce visualisation for implant positioning. Computer-assisted orthopaedic surgical strategies were developed to enhance placement of implants by conventional methods,<sup>126</sup> but they are now used to improve outcome of minimally invasive surgery.<sup>127,128</sup> Long-term follow-up is needed to show that the proven durability of total hip replacement is not being lost by compromised exposure.

## Outcome assessment

30 years ago, the main indications for total hip replacement were pain, disability, or both. Outcome assessment was surgeon-based with hip scores. Charnley's modification of the Merle d'Aubigné and Postel score<sup>129</sup> and the Harris hip score<sup>130</sup> remain two of the most widely used methods. An inherent difficulty of most surgeon-based scoring systems for assessment of outcomes is that they are composite scores, which include clinical and radiological data together with patient-based subjective information. Scores allocated within a criterion are not proportional and cannot then be added together in a meaningful way.

Survivorship analysis, first used in orthopaedics by Dobbs in 1980,<sup>131</sup> is a powerful strategy for long-term assessment of replacement arthroplasty. It uses a defined endpoint (revision of implant, etc) and is useful to assess and compare survivorship of different types of implants. The Kaplan-Meier<sup>132</sup> method is most frequently used to construct survival plots. Although revision is a reproducible endpoint, it can be affected by extraneous factors such as age or fitness for surgery. Even inclusion of other endpoints such as presence of severe pain, low functional scores, and radiographic evidence of loosening gives no information about patient's satisfaction or health-related quality of life. There is sometimes substantial disagreement between doctors and patients about health status.<sup>133</sup>

An unacceptable compromise in quality of life represents the main indication for total hip replacement in many individuals presenting today. Thus, only patient-based measures can be used to assess patient's satisfaction with health-related quality of life postoperatively.

Traditionally, generic scales that measure general health status (eg, short form 12)<sup>134</sup> and disease-specific scores that assess outcomes important to patients (eg, the Western Ontario and McMaster University osteoarthritis index)<sup>135</sup> are used in clinical trials of total hip replacements. Furthermore, site-specific measures have been used as a primary endpoint after surgery. Thus, the Oxford hip score<sup>136</sup> is a short, practical, valid, and reliable questionnaire that is sensitive to clinically important changes and is well accepted by patients.

These patient-based assessment methods provide a numerical endpoint that defines clinical outcome. However, they are not patient-specific and do not provide information about what is important to the individual and whether their preoperative expectations have been met. For example, a 65-year-old golfer who remains unable to complete 18 holes after a primary hip replacement might well regard the operation as a failure despite a hip score that would categorise him as good or excellent. Patient's satisfaction can therefore be poor if expectations are not met. Conversely, a 25-year-old juvenile idiopathic arthritis patient confined to bed or chair whose surgery has restored domestic independence, with commensurate improvement in quality of life,

would judge the surgery a great success, despite a very poor hip score.

The personal impact health assessment questionnaire<sup>137</sup> was developed to assess the individual effect of disability in patients with rheumatoid arthritis. A similar personalised scoring system is being developed and validated for people with osteoarthritis.<sup>138</sup> Wright and colleagues<sup>139</sup> have used a somewhat cumbersome patient-generated questionnaire that identifies the main concerns of the individual and how these are affected by surgery.

Methods to assess personal effect on disability will not only expose any adverse events or failures associated with surgery but also identify whether realistic expectations discussed preoperatively have been achieved postoperatively. These procedures truly indicate the patient's assessment of outcome.

## Discussion

Biological resurfacing of the hip joint with engineered tissue is at present no more than a theoretical possibility. Total hip replacement will therefore remain the treatment of choice for arthritis of the hip for the foreseeable future. Both cemented and cementless implants can provide good fixation with favourable long-term results. Today, uncemented prostheses are preferred globally, although this choice is not evidence based and might be less cost effective than cemented implants.

Ultrahigh-molecular-weight polyethylene has been the most widely used material for the acetabular bearing. Wear of the polyethylene counterface results in osteolysis and impingement, both of which culminate in aseptic loosening. Harris<sup>140</sup> has described the unravelling of the biological process and the prevention of osteolysis. While this optimism is perhaps somewhat premature, durable low-wear articular couples are available today that permit use of large heads to deliver both mobility and stability. Moreover, new drugs are being developed that will prevent osteolysis and loss of bone. As noted, new materials such as Oxinium provide enhanced wear resistance and durability of the articulation. Lappalainen and Santavirta<sup>141</sup> have predicted that novel coatings will further improve the longevity of total hip replacements.

The idea behind minimally invasive surgery embraces both soft-tissue sparing and bone conservation. Conservative femoral implants take less bone at surgery and preserve bone in the long term by providing more physiological loading of the proximal femur. The ability to revise these prostheses to primary standard stems introduces an additional option in the revision programme for the young patient. Furthermore, short stems are easy to insert with minimally invasive surgery, with reduced soft-tissue damage and accelerated rehabilitation. Despite reports of "catastrophic complications of minimally invasive hip surgery",<sup>142</sup> Berry has noted that "It remains difficult to escape the commonsense logic that less invasive operative methods



can provide benefits for patients".<sup>143</sup> Short-term gains delivered by this strategy will hopefully not be achieved at the expense of long-term survivorship.

Computer-assisted orthopaedic surgery produces better component orientation than the best unaided efforts of the skilled hip surgeon. This technique could reduce the rate of complications (dislocation) and enhance long-term survivorship. Advanced technology has made computer-assisted surgery user friendly.<sup>144</sup> Although prospective randomised trials are needed, the reproducible improvement in component orientation that has been shown is likely to lead to widespread use of computer assistance. Patients' benefit and the unwanted attentions of litigation lawyers are also likely to increase use of computer-assisted surgery in the foreseeable future.

Patients' expectations after total hip replacement have changed. Today, quality of life issues, which sometimes include high-activity recreational interests, define their aspirations. Modern technology can deliver high-performance hips to accommodate these expectations—but at a cost. Ultimately, health economics will dictate what is both affordable and cost effective in any health-care system.

#### Conflict of interest statement

IDL is a consultant for DePuy International and has received research funding from DePuy, Stryker, Endoplus, and Zimmer. CR has been a consultant for Smith & Nephew.

#### References

- Buchanan WW, Dequeker J. History of rheumatic diseases (ch 1). In: Klippel JH, Dieppe PA, eds. *Rheumatology*. Philadelphia: Mosby, 1998: 1–5.
- Berato J, Dutour O, Williams J, Zakarian H, Acquaviva PC. [Epidemiology of rheumatic diseases in an ancient population: study of the Necropole du Haut-Empire de Saint-Lambert (Frejus, Var)]. *Rev Rhum Mal Osteoartic* 1990; **57**: 397–400.
- Smith-Petersen MN. The classic: evolution of mould arthroplasty of the hip joint. *J Bone Joint Surg* 1948; **30B**: L59.
- Wiles P. The surgery of the osteoarthritic hip. *Br J Surg* 1958; **45**: 488–97.
- Charnley J. Arthroplasty of the hip: a new operation. *Lancet* 1961; **1**: 1129–32.
- Berry DJ, Harmsen WS, Cabanela ME, Morrey BF. Twenty-five-year survivorship of two thousand consecutive primary Charnley total hip replacements: factors affecting survivorship of acetabular and femoral components. *J Bone Joint Surg Am* 2002; **84A**: 171–77.
- Callaghan JJ, Albright JC, Goetz DD, Olejniczak JP, Johnston RC. Charnley total hip arthroplasty with cement: minimum twenty-five-year follow-up. *J Bone Joint Surg Am* 2000; **82**: 487–97.
- Wroblewski BM, Fleming PA, Siney PD. Charnley low-friction torque arthroplasty of the hip: 20-to-30 year results. *J Bone Joint Surg Br* 1999; **81**: 427–30.
- Kavanagh BF, Wallrichs S, Dewitz M, et al. Charnley low-friction arthroplasty of the hip: twenty-year results with cement. *J Arthroplasty* 1994; **9**: 229–34.
- Older J. Charnley low-friction arthroplasty: a worldwide retrospective review at 15 to 20 years. *J Arthroplasty* 2002; **17**: 675–80.
- Coventry MB. Foreword. In Amutz HC, ed. *Hip arthroplasty*. New York: Churchill Livingstone, 1991.
- Fender D, Harper WM, Gregg PJ. Outcome of Charnley total hip replacement across a single health region in England: the results at five years from a regional hip register. *J Bone Joint Surg Br* 1999; **81**: 577–81.
- Charnley J. Fracture of femoral prostheses in total hip replacement: a clinical study. *Clin Orthop Relat Res* 1975; **111**: 105–20.
- Charnley J. Long-term clinical results. In: *Low friction arthroplasty of the hip: theory and practice*. New York: Springer-Verlag, 1979.
- Eftekhar NS. Long-term results of cemented total hip arthroplasty. *Clin Orthop Relat Res* 1987; **225**: 207–17.
- Wroblewski BM. Direction and rate of socket wear in Charnley low-friction arthroplasty. *J Bone Joint Surg Br* 1985; **67**: 757–61.
- Woo RY, Morrey BF. Dislocations after total hip arthroplasty. *J Bone Joint Surg Am* 1982; **64**: 1295–306.
- Dorr LD, Luckett M, Conaty JP. Total hip arthroplasties in patients younger than 45 years: a nine- to ten-year follow-up study. *Clin Orthop Relat Res* 1990; **260**: 215–19.
- Malchau H, Herberts P, Garellick G, Soderman P, Eisler T. Prognosis of total hip replacement: update of results and risk-ratio analysis for revision and re-revision from the Swedish National Hip Arthroplasty Register 1979–2000—Presented at the 69th Annual Meeting of the American Orthopaedic Surgeons; February 13–27, 2002; Dallas, TX, USA.
- Chandler HP, Reineck FT, Wixson RL, McCarthy JC. Total hip replacement in patients younger than thirty years old: a five-year follow-up study. *J Bone Joint Surg Am* 1981; **63**: 1426–34.
- Glück T. Referat über die durch das moderne chirurgische experiment gewonnenen positiven resultaten, betreffende die naht und den ersatz von defekten höherer gewebe, sowie über die verwerthung resorbirbarer und lebendiger tampons in der chirurgie. *Arch Klin Chir* 1891; **41**: 187–239.
- Charnley J. Anchorage of the femoral head prosthesis to the shaft of the femur. *J Bone Joint Surg Br* 1960; **42B**: 28–30.
- Askew MJ, Steege JW, Lewis JL, Ranieri JR, Wixson RL. Effect of cement pressure and bone strength on polymethylmethacrylate fixation. *J Orthop Res* 1984; **1**: 412–20.
- Krause WR, Krug W, Miller J. Strength of the cement-bone interface. *Clin Orthop Relat Res* 1982; **163**: 290–99.
- Majkowski RS, Miles AW, Bannister GC, Perkins J, Taylor GJ. Bone surface preparation in cemented joint replacement. *J Bone Joint Surg Br* 1993; **75**: 459–63.
- Breusch SJ, Norman TL, Schneider U, Reitzel T, Blaha JD, Lukoschek M. Lavage technique in total hip arthroplasty: jet lavage produces better cement penetration than syringe lavage in the proximal femur. *J Arthroplasty* 2000; **15**: 921–27.
- Gozzard C, Gheduzzi S, Miles AW, Learmonth ID. An in-vitro investigation of the CPS-Plus femoral stem: influence of the proximal centraliser on cement pressurisation during stem insertion. *Acta Orthop Scand* 2003; **74**: 154–58.
- Herberts P, Malchau H. Long-term registration has improved the quality of hip replacement: a review of the Swedish THR Register comparing 160000 cases. *Acta Orthop Scand* 2000; **71**: 111–21.
- Mulroy RD Jr, Harris WH. The effect of improved cementing techniques on component loosening in total hip replacement: an 11-year radiographic review. *J Bone Joint Surg Br* 1990; **72**: 757–60.
- Williams HD, Browne G, Gie GA, Ling RS, Timperley AJ, Wendover NA. The Exeter universal cemented femoral component at 8 to 12 years: a study of the first 325 hips. *J Bone Joint Surg Br* 2002; **84**: 324–34.
- Wroblewski BM, Siney PD, Fleming PA. Triple taper polished cemented stem in total hip arthroplasty: rationale for the design, surgical technique, and 7 years of clinical experience. *J Arthroplasty* 2001; **16** (8 suppl 1): 37–41.
- Langlais F, Kerboull M, Sedel L, Ling RS. The 'French paradox'. *J Bone Joint Surg Br* 2003; **85**: 17–20.
- Charnley J. The long-term results of low-friction arthroplasty of the hip performed as a primary intervention. *J Bone Joint Surg Br* 1972; **54**: 61–76.
- Dall DM, Learmonth ID, Solomon MI, Miles AW, Davenport JM. Fracture and loosening of Charnley femoral stems: comparison between first-generation and subsequent designs. *J Bone Joint Surg Br* 1993; **75**: 259–65.
- Malchau H, Herberts P. Prognosis of total hip replacement: surgical and cementing technique in THR—a revision-risk study of 134056 primary operations. 63rd Annual Meeting of the American Academy of Orthopaedic Surgeons; 22–25 February, 1996; Atlanta, GA, USA.

- 36 Massoud SN, Hunter JB, Holdsworth BJ, Wallace WA, Juliusson R. Early femoral loosening in one design of cemented hip replacement. *J Bone Joint Surg Br* 1997; **79**: 603–08.
- 37 Havelin LI, Espehaug B, Engesaeter LB. The performance of two hydroxyapatite-coated acetabular cups compared with Charnley cups: from the Norwegian Arthroplasty Register. *J Bone Joint Surg Br* 2002; **84**: 839–45.
- 38 Gie GA, Hoe F, Timperley AJ, Ling RSM. The Exeter polished stem in the longer term: a survivorship study to the 33rd year of follow-up and a study of stem subsistence. *European Hip Society*; 23–26 June, 2004; Innsbruck, Austria.
- 39 Spitzer AI. The cemented femoral stem: selecting the ideal patient. *Orthopedics* 2005; **28** (8 suppl): S841–48.
- 40 Charnley J. Long-term radiological results. In: *Low friction arthroplasty of the hip: theory and practice*. New York: Springer-Verlag, 1979.
- 41 Harris WH, Schiller AL, Scholler JM, Freiberg RA, Scott R. Extensive localized bone resorption in the femur following total hip replacement. *J Bone Joint Surg Am* 1976; **58**: 612–18.
- 42 Maloney WJ, Jasty M, Rosenberg A, Harris WH. Bone lysis in well-fixed cemented femoral components. *J Bone Joint Surg Br* 1990; **72**: 966–70.
- 43 Jasty MJ, Floyd WE III, Schiller AL, Goldring SR, Harris WH. Localized osteolysis in stable, non-septic total hip replacement. *J Bone Joint Surg Am* 1986; **68**: 912–19.
- 44 Jones LC, Hungerford DS. Cement disease. *Clin Orthop Relat Res* 1987; **225**: 192–206.
- 45 Lavernia C, D'Apuzzo M, Hernandez V, Lee D. Thigh pain in primary total hip arthroplasty: the effects of elastic moduli. *J Arthroplasty* 2004; **19** (7 suppl 2): 10–16.
- 46 Bourne RB, Rorabeck CH, Ghazal ME, Lee MH. Pain in the thigh following total hip replacement with a porous-coated anatomic prosthesis for osteoarthritis: a five-year follow-up study. *J Bone Joint Surg Am* 1994; **76**: 1464–70.
- 47 Keaveny TM, Bartel DL. Mechanical consequences of bone ingrowth in a hip prosthesis inserted without cement. *J Bone Joint Surg Am* 1995; **77**: 911–23.
- 48 Schmalzried TP, Jasty M, Harris WH. Periprosthetic bone loss in total hip arthroplasty: polyethylene wear debris and the concept of the effective joint space. *J Bone Joint Surg Am* 1992; **74**: 849–63.
- 49 McAuley JP, Culpepper WJ, Eng C. Total hip arthroplasty: concerns with extensively porous coated femoral components. *Clin Orthop Relat Res* 1998; **355**: 182–88.
- 50 Campbell AC, Rorabeck CH, Bourne RB, Chess D, Nott L. Thigh pain after cementless hip arthroplasty: annoyance or ill omen. *J Bone Joint Surg Br* 1992; **74**: 63–66.
- 51 Bourne RB, Rorabeck CH, Patterson JJ, Guerin J. Tapered titanium cementless total hip replacements: a 10- to 13-year followup study. *Clin Orthop Relat Res* 2001; **393**: 112–20.
- 52 Reitman RD, Emerson R, Higgins L, Head W. Thirteen year results of total hip arthroplasty using a tapered titanium femoral component inserted without cement in patients with type C bone. *J Arthroplasty* 2003; **18** (7 suppl 1): 116–21.
- 53 Parvizi J, Keisu KS, Hozack WJ, Sharkey PF, Rothman RH. Primary total hip arthroplasty with an uncemented femoral component: a long-term study of the Taperloc stem. *J Arthroplasty* 2004; **19**: 151–56.
- 54 Barrack RL, Mulroy RD Jr, Harris WH. Improved cementing techniques and femoral component loosening in young patients with hip arthroplasty: a 12-year radiographic review. *J Bone Joint Surg Br* 1992; **74**: 385–89.
- 55 Capello WN, Colyer RA, Kernek CB, Carnahan JV, Hess JJ. Failure of the Mecron screw-in ring. *J Bone Joint Surg Br* 1993; **75**: 835–36.
- 56 Fox GM, McBeath AA, Heiner JP. Hip replacement with a threaded acetabular cup: a follow-up study. *J Bone Joint Surg Am* 1994; **76**: 195–201.
- 57 Udomkiat P, Dorr LD, Wan Z. Cementless hemispheric porous-coated sockets implanted with press-fit technique without screws: average ten-year follow-up. *J Bone Joint Surg Am* 2002; **84A**: 1195–200.
- 58 Clohisy JC, Harris WH. The Harris-Galante porous-coated acetabular component with screw fixation: an average ten-year follow-up study. *J Bone Joint Surg Am* 1999; **81**: 66–73.
- 59 Ries MD, Collis DK, Lynch F. Separation of the polyethylene liner from acetabular cup metal backing: a report of three cases. *Clin Orthop Relat Res* 1992; **282**: 164–69.
- 60 Barrack RL, Burke DW, Cook SD, Skinner HB, Harris WH. Complications related to modularity of total hip components. *J Bone Joint Surg Br* 1993; **75**: 688–92.
- 61 Gonzalez della Valle A, Ruzo PS, Li S, Pellicci P, Sculco TP, Salvati EA. Dislodgment of polyethylene liners in first and second-generation Harris-Galante acetabular components: a report of eighteen cases. *J Bone Joint Surg Am* 2001; **83A**: 553–59.
- 62 Louwse RT, Heyligers IC. Late failure of the polyethylene liner fixation in an uncemented total hip arthroplasty. *J Arthroplasty* 1999; **14**: 391–96.
- 63 Duffy P, Sher JL, Partington PF. Premature wear and osteolysis in an HA-coated, uncemented total hip arthroplasty. *J Bone Joint Surg Br* 2004; **86**: 34–38.
- 64 Cook SD, Barrack RL, Thomas KA, Haddad RJ Jr. Quantitative analysis of tissue growth into human porous total hip components. *J Arthroplasty* 1988; **3**: 249–62.
- 65 Freeman MA. Hydroxyapatite: catalyst or conjurer? *Orthopedics* 1998; **21**: 959–62.
- 66 Rasquinha VJ, Ranawat CS, Mauriello AJ Jr. Hydroxyapatite: catalyst or conjurer? *J Arthroplasty* 2002; **17** (4 suppl 1): 113–17.
- 67 D'Antonio JA, Capello WN, Manley MT, Geesink R. Hydroxyapatite femoral stems for total hip arthroplasty: 10- to 13-year followup. *Clin Orthop Relat Res* 2001; **393**: 101–11.
- 68 Herberts P, Kärrholm J, Garellick G. The Swedish National Hip Arthroplasty Register: annual report 2004. Sahlgrenska: Sahlgrenska University Hospital, 2005. Available at: <http://www.jru.orthop.gu.se/documents.htm> (accessed Dec 13, 2006).
- 69 Kim YH. Long-term results of the cementless porous-coated anatomic total hip prosthesis. *J Bone Joint Surg Br* 2005; **87**: 623–27.
- 70 Capello WN, D'Antonio JA, Feinberg JR, Manley MT. Ten-year results with hydroxyapatite-coated total hip femoral components in patients less than fifty years old: a concise follow-up of a previous report. *J Bone Joint Surg Am* 2003; **85A**: 885–89.
- 71 Kearns SR, Jamal B, Rorabeck CH, Bourne RB. Factors affecting survival of uncemented total hip arthroplasty in patients 50 years or younger. *Clin Orthop Relat Res* 2006; **453**: 103–09.
- 72 Bragdon CR, Doherty AM, Rubash HE, et al. The efficacy of BMP-2 to induce bone ingrowth in a total hip replacement model. *Clin Orthop Relat Res* 2003; **417**: 50–61.
- 73 Bragdon CR, Jasty M, Greene M, Rubash HE, Harris WH. Biologic fixation of total hip implants: insights gained from a series of canine studies. *J Bone Joint Surg Am* 2004; **86A** (suppl 2): 105–17.
- 74 Jasty M, Rubash HE, Paiement GD, Bragdon CR, Parr J, Harris WH. Porous-coated uncemented components in experimental total hip arthroplasty in dogs: effect of plasma-sprayed calcium phosphate coatings on bone ingrowth. *Clin Orthop Relat Res* 1992; **280**: 300–09.
- 75 Maloney WJ, Jasty M, Harris WH, Galante JO, Callaghan JJ. Endosteal erosion in association with stable uncemented femoral components. *J Bone Joint Surg Am* 1990; **72**: 1025–34.
- 76 Vernon-Roberts B, Freeman MAR. The tissue response to total joint replacement prostheses. In: Swanson SAV, Freeman MAR, eds. *The scientific basis of joint replacement*. Tunbridge Wells: Pitman Medical Publishing, 1977: p 86–129.
- 77 Willert HG. Reactions of the articular capsule to wear products of artificial joint prostheses. *J Biomed Mater Res* 1977; **11**: 157–64.
- 78 Archibeck MJ, Jacobs JJ, Roebuck KA, Glant TT. The basic science of periprosthetic osteolysis. *Instr Course Lect* 2001; **50**: 185–95.
- 79 Amstutz HC, Campbell P, Kossovsky N, Clarke IC. Mechanism and clinical significance of wear debris-induced osteolysis. *Clin Orthop Relat Res* 1992; **276**: 7–18.
- 80 Green TR, Fisher J, Stone M, Wroblewski BM, Ingham E. Polyethylene particles of a 'critical size' are necessary for the induction of cytokines by macrophages in vitro. *Biomaterials* 1998; **19**: 2297–302.
- 81 Ries MD, Scott ML, Jani S. Relationship between gravimetric wear and particle generation in hip simulators: conventional compared with cross-linked polyethylene. *J Bone Joint Surg Am* 2001; **83A** (2 suppl 2): 116–22.

- 82 Saikko V, Calonius O, Keranen J. Wear of conventional and cross-linked ultra-high-molecular-weight polyethylene acetabular cups against polished and roughened CoCr femoral heads in a biaxial hip simulator. *J Biomed Mater Res* 2002; **63**: 848–53.
- 83 D'Antonio JA, Manley MT, Capello WN, et al. Five-year experience with Crossfire highly cross-linked polyethylene. *Clin Orthop Relat Res* 2005; **441**: 143–50.
- 84 McKee GK, Watson-Farrar J. Replacement of arthritic hips by the McKee-Farrar prosthesis. *J Bone Joint Surg Br* 1966; **48**: 245–59.
- 85 Ring PA. Complete replacement arthroplasty of the hip by the ring prosthesis. *J Bone Joint Surg Br* 1968; **50**: 720–31.
- 86 Muller ME. Total hip prostheses. *Clin Orthop Relat Res* 1970; **72**: 46–68.
- 87 Jacobsson SA, Djerf K, Wahlstrom O. Twenty-year results of McKee-Farrar versus Charnley prosthesis. *Clin Orthop Relat Res* 1996; **329** (suppl): S60–68.
- 88 Schmalzried TP, Peters PC, Maurer BT, Bragdon CR, Harris WH. Long-duration metal-on-metal total hip arthroplasties with low wear of the articulating surfaces. *J Arthroplasty* 1996; **11**: 322–31.
- 89 McKellop H, Park SH, Chiesa R, et al. In vivo wear of three types of metal on metal hip prostheses during two decades of use. *Clin Orthop Relat Res* 1996; **329** (suppl): S128–40.
- 90 Naudie D, Roeder CP, Parvizi J, Berry DJ, Egli S, Busato A. Metal-on-metal versus metal-on-polyethylene bearings in total hip arthroplasty: a matched case-control study. *J Arthroplasty* 2004; **19** (7 suppl 2): 35–41.
- 91 Brodner W, Bitzan P, Meisinger V, Kaider A, Gottsauner-Wolf F, Kotz R. Elevated serum cobalt with metal-on-metal articulating surfaces. *J Bone Joint Surg Br* 1997; **79**: 316–21.
- 92 Macdonald SJ, McCalden RW, Chess DG, et al. Metal-on-metal versus polyethylene in hip arthroplasty: a randomized clinical trial. *Clin Orthop Relat Res* 2003; **406**: 282–96.
- 93 Clarke MT, Lee PT, Arora A, Villar RN. Levels of metal ions after small- and large-diameter metal-on-metal hip arthroplasty. *J Bone Joint Surg Br* 2003; **85**: 913–17.
- 94 Harding I, Bonomo A, Crawford R, et al. Serum levels of cobalt and chromium in a complex modular total hip arthroplasty system. *J Arthroplasty* 2002; **17**: 893–95.
- 95 Semlitsch M, Willert HG. Clinical wear behaviour of ultra-high molecular weight polyethylene cups paired with metal and ceramic ball heads in comparison to metal-on-metal pairings of hip joint replacements. *Proc Inst Mech Eng [H]* 1997; **211**: 73–88.
- 96 Lerouge S, Huk O, Yahia L, Witvoet J, Sedel L. Ceramic-ceramic and metal-polyethylene total hip replacements: comparison of pseudomembranes after loosening. *J Bone Joint Surg Br* 1997; **79**: 135–39.
- 97 Fritsch EW, Gleitz M. Ceramic femoral head fractures in total hip arthroplasty. *Clin Orthop Relat Res* 1996; **328**: 129–36.
- 98 Callaway GH, Flynn W, Ranawat CS, Sculco TP. Fracture of the femoral head after ceramic-on-polyethylene total hip arthroplasty. *J Arthroplasty* 1995; **10**: 855–59.
- 99 D'Antonio J, Capello W, Manley M, Naughton M, Sutton K. Alumina ceramic bearings for total hip arthroplasty: five-year results of a prospective randomized study. *Clin Orthop Relat Res* 2005; **436**: 164–71.
- 100 Bourne RB, Barrack R, Rorabeck CH, Salehi A, Good V. Arthroplasty options for the young patient: Oxinium on cross-linked polyethylene. *Clin Orthop Relat Res* 2005; **441**: 159–67.
- 101 Good V, Ries M, Barrack RL, Widding K, Hunter G, Heuer D. Reduced wear with oxidized zirconium femoral heads. *J Bone Joint Surg Am* 2003; **85A** (suppl 4): 105–10.
- 102 Jolley MN, Salvati EA, Brown GC. Early results and complications of surface replacement of the hip. *J Bone Joint Surg Am* 1982; **64**: 366–77.
- 103 Bell RS, Schatzker J, Fornasier VL, Goodman SB. A study of implant failure in the Wagner resurfacing arthroplasty. *J Bone Joint Surg Am* 1985; **67**: 1165–75.
- 104 Head WC. Wagner surface replacement arthroplasty of the hip: analysis of fourteen failures in forty-one hips. *J Bone Joint Surg Am* 1981; **63**: 420–27.
- 105 Freeman MA, Cameron HU, Brown GC. Cemented double cup arthroplasty of the hip: a 5 year experience with the ICLH prosthesis. *Clin Orthop Relat Res* 1978; **134**: 45–52.
- 106 McMinn D, Treacy R, Lin K, Pynsent P. Metal on metal surface replacement of the hip: experience of the McMinn prosthesis. *Clin Orthop Relat Res* 1996; **329** (suppl): S89–98.
- 107 Treacy RB, McBryde CW, Pynsent PB. Birmingham hip resurfacing arthroplasty: a minimum follow-up of five years. *J Bone Joint Surg Br* 2005; **87**: 167–70.
- 108 Shimmin AJ, Back D. Femoral neck fractures following Birmingham hip resurfacing: a national review of 50 cases. *J Bone Joint Surg Br* 2005; **87**: 463–64.
- 109 Amstutz HC, Campbell PA, Le Duff MJ. Fracture of the neck of the femur after surface arthroplasty of the hip. *J Bone Joint Surg Am* 2004; **86A**: 1874–77.
- 110 Beaulé PE, Dorey FJ, LeDuff M, Gruen T, Amstutz HC. Risk factors affecting outcome of metal-on-metal surface arthroplasty of the hip. *Clin Orthop Relat Res* 2004; **418**: 87–93.
- 111 Eastaugh-Waring SJ, Seenath S, Learmonth DS, Learmonth ID. The practical limitations of resurfacing hip arthroplasty. *J Arthroplasty* 2006; **21**: 18–22.
- 112 Malchau H, Herberts P, Eisler T, Garellick G, Soderman P. The Swedish Total Hip Replacement Register. *J Bone Joint Surg Am* 2002; **84A** (suppl 2): 2–20.
- 113 Dorr LD, Kane TJ III, Conaty JP. Long-term results of cemented total hip arthroplasty in patients 45 years old or younger: a 16-year follow-up study. *J Arthroplasty* 1994; **9**: 453–56.
- 114 Engh CA, Bobyn JD, Glassman AH. Porous-coated hip replacement: the factors governing bone ingrowth, stress shielding, and clinical results. *J Bone Joint Surg Br* 1987; **69**: 45–55.
- 115 Tennent TD, Goddard NJ. Current attitudes to total hip replacement in the younger patient: results of a national survey. *Ann R Coll Surg Engl* 2000; **82**: 33–38.
- 116 Huggler AH, Jacob HA, Bereiter H, Haferkorn M, Ryf C, Schenk R. Long-term results with the uncemented thrust plate prosthesis (TPP). *Acta Orthop Belg* 1993; **59** (suppl 1): 215–23.
- 117 Buergi ML, Stoffel KK, Jacob HA, Bereiter HH. Radiological findings and clinical results of 102 thrust-plate femoral hip prostheses: a follow-up of 2 to 8 years. *J Arthroplasty* 2005; **20**: 108–17.
- 118 Morrey BF, Adams RA, Kessler M. A conservative femoral replacement for total hip arthroplasty: a prospective study. *J Bone Joint Surg Br* 2000; **82**: 952–58.
- 119 Berry DJ, Berger RA, Callaghan JJ, et al. Minimally invasive total hip arthroplasty: development, early results, and a critical analysis—presented at the Annual Meeting of the American Orthopaedic Association, Charleston, South Carolina, USA, June 14, 2003. *J Bone Joint Surg Am* 2003; **85A**: 2235–46.
- 120 NICE. Single mini-incision hip replacement: interventional procedure guidance 152. London: National Institute for Health and Clinical Excellence, 2006.
- 121 Ogonda L, Wilson R, Archbold P, et al. A minimal-incision technique in total hip arthroplasty does not improve early postoperative outcomes: a prospective, randomized, controlled trial. *J Bone Joint Surg Am* 2005; **87**: 701–10.
- 122 Chimento GF, Pavone V, Sharrock N, Kahn B, Cahill J, Sculco TP. Minimally invasive total hip arthroplasty: a prospective randomized study. *J Arthroplasty* 2005; **20**: 139–44.
- 123 Berger RA, Duwelius PJ. The two-incision minimally invasive total hip arthroplasty: technique and results. *Orthop Clin North Am* 2004; **35**: 163–72.
- 124 Bal BS, Haltom D, Aleto T, Barrett M. Early complications of primary total hip replacement performed with a two-incision minimally invasive technique. *J Bone Joint Surg Am* 2005; **87**: 2432–38.
- 125 NICE. Minimally invasive two-incision surgery for total hip replacement: interventional procedure guidance 112. London: National Institute for Clinical Excellence, 2005.
- 126 Stiehl JB, Konermann WH, Haaker RGA. Navigation and robotics in total joint and spine surgery. New York: Springer-Verlag, 2003.
- 127 DiGioia AM III, Jaramaz B, Plakseychuk AY, et al. Comparison of a mechanical acetabular alignment guide with computer placement of the socket. *J Arthroplasty* 2002; **17**: 359–64.
- 128 Nogler M. Navigated minimal invasive total hip arthroplasty. *Surg Technol Int* 2004; **12**: 259–62.

- 129 Charnley J. The long-term results of low-friction arthroplasty of the hip performed as a primary intervention. *J Bone Joint Surg Br* 1972; **54B**: 61–76.
- 130 Harris WH. Traumatic arthritis of the hip after dislocation and acetabular fractures: treatment by mold arthroplasty—an end-result study using a new method of result evaluation. *J Bone Joint Surg Am* 1969; **51**: 737–55.
- 131 Dobbs HS. Survivorship of total hip replacements. *J Bone Joint Surg Br* 1980; **62B**: 168–73.
- 132 Kaplan EL, Meier P. Nonparametric estimation from incomplete observations. *J Am Stat Assoc* 1958; **53**: 457–81.
- 133 Janse AJ, Gemke RJ, Uiterwaal CS, van der Tweel I, Kimpen JL, Sinnema G. Quality of life: patients and doctors don't always agree: a meta-analysis. *J Clin Epidemiol* 2004; **57**: 653–61.
- 134 Ware JE, Kosinski M, Keller SD. The SF-12: an even shorter health survey. <http://www.sf-36.org/tools/sf12.shtml> (accessed Dec 13, 2006).
- 135 Bellamy N, Buchanan WW, Goldsmith CH, Campbell J, Stitt LW. Validation study of WOMAC: a health status instrument for measuring clinically important patient relevant outcomes to antirheumatic drug therapy in patients with osteoarthritis of the hip or knee. *J Rheumatol* 1988; **15**: 1833–40.
- 136 Dawson J, Fitzpatrick R, Carr A, Murray D. Questionnaire on the perceptions of patients about total hip replacement. *J Bone Joint Surg Br* 1996; **78**: 185–90.
- 137 Hewlett S, Smith AP, Kirwan JR. Measuring the meaning of disability in rheumatoid arthritis: the personal impact health assessment questionnaire (PI HAQ). *Ann Rheum Dis* 2002; **61**: 986–93.
- 138 Wylde V, Hewlett S, Learmonth ID, Cavendish VJ. Personal impact of disability in osteoarthritis: patient, professional and public values. *Musculoskeletal Care* 2006; **4**: 152–66.
- 139 Wright JG, Rudicel S, Feinstein AR. Ask patients what they want: evaluation of individual complaints before total hip replacement. *J Bone Joint Surg Br* 1994; **76**: 229–34.
- 140 Harris WH. Conquest of a worldwide human disease: particle-induced periprosthetic osteolysis. *Clin Orthop Relat Res* 2004; **429**: 39–42.
- 141 Lappalainen R, Santavirta SS. Potential of coatings in total hip replacement. *Clin Orthop Relat Res* 2005; **430**: 72–79.
- 142 Fehring TK, Mason JB. Catastrophic complications of minimally invasive hip surgery: a series of three cases. *J Bone Joint Surg Am* 2005; **87**: 711–14.
- 143 Berry DJ. Minimally invasive total hip arthroplasty. *J Bone Joint Surg Am* 2005; **87**: 699–700.
- 144 DiGioia AM III, Jaramaz B, Colgan BD. Computer assisted orthopaedic surgery: image guided and robotic assistive technologies. *Clin Orthop Relat Res* 1998; **354**: 8–16.