The influence of the size of the component on the outcome of resurfacing arthroplasty of the hip

A REVIEW OF THE LITERATURE

The survivorship of contemporary resurfacing arthroplasty of the hip using metal-on-metal bearings is better than that of first generation designs, but short-term failures still occur. The most common reasons for failure are fracture of the femoral neck, loosening of the component, osteonecrosis of the femoral head, reaction to metal debris and malpositioning of the component. In 2008 the Australian National Joint Registry reported an inverse relationship between the size of the head component and the risk of revision in resurfacing hip arthroplasty. Hips with a femoral component size of $\leq 44$ mm have a fivefold increased risk of revision than those with femoral components of $\geq 55$ mm irrespective of gender. We have reviewed the literature to explore this observation and to identify possible reasons including the design of the implant, loading of the femoral neck, the orientation of the component, the production of wear debris and the effects of metal ions, penetration of cement and vascularity of the femoral head. Our conclusion is that although multifactorial, the most important contributors to failure in resurfacing arthroplasty of the hip are likely to be the design and geometry of the component and the orientation of the acetabular component.

In 2008, the Australian Orthopaedic Association National Joint Replacement Registry identified an inverse relationship between the size of the femoral component and the risk of revision for hip resurfacing arthroplasty. A fivefold increase in the incidence of the revision of hips was noted when a femoral component smaller than 44 mm was used, as opposed to 55 mm or larger. This finding was true for both men and women and, after accounting for the size of the component, survivorship was found to be independent of gender.

The influence of size on failure was also identified during the evaluation of the historical metal-on-polyethylene Tharies hip resurfacing in which the size of the bearing was the only factor influencing survival. More recently, Beaule et al explored the link between body-weight and outcome in assessing risk factors affecting the outcome of resurfacing arthroplasty of the hip. They found an inverse relationship between body-weight and the risk of an adverse outcome, with lower body-weight being associated with a smaller size of component.

We have reviewed published studies relating to the observed relationship between size and the survivorship for this procedure. Many reports are limited in their evaluation of the size of the head as a specific factor in the outcome. We attempt to explain the increased revision rate of smaller components by considering the possible roles of the design of the implant, loading of the femoral neck, penetration of cement, the production of wear debris, the effects of orientation of the component and the vascularity of the femoral head.

We carried out a systematic review of the literature using references to resurfacing arthroplasty of the hip from the Medline bibliographic database. An initial search was performed using the keywords ‘hip resurfacing’ or ‘resurfacing arthroplasty’. Review articles and the bibliographies of each reference were also searched to find additional articles which appeared to be relevant. The initial Medline search identified over 450 references that related to resurfacing arthroplasty of the hip. Manuscripts were initially excluded if their contents did not address the study hypothesis, were in a foreign language, or were methods papers or case reports. This resulted in a subset of 114 references. Articles were further excluded if the pertinent information they provided was consistent and substantially similar to other included references. Emphasis was placed on studies with larger patient populations, more recent publi-
cation dates and higher impact journals. As a result of those exclusions, we specifically examined 59 references which described the mechanism of failure of resurfacing arthroplasty of the hip and the incidence or mechanisms of failure based on the size of the implanted component the gender of the patient.

The role of the design of the implant
There is a broad choice of resurfacing prostheses currently available with subtle differences in design according to material composition, dimensions of the stem, geometry and fixation, all of which have a role in the performance of the device.

If resurfacing arthroplasty of the hip is to bone conserve, it demands minimal removal of acetabular bone. In order to achieve bone conservation and an implant of minimal thickness. Generally, the difference between the inner and outer diameter of the acetabular and femoral components is 6 mm each, producing a combined thickness of the resurfacing construct of 12 mm. Most manufacturers maintain the same thickness throughout the range of sizes which means that the combined thickness of the implant is relatively more in the smaller sizes (Figs 1 and 2). When using components of smaller size, determination of the size of the implant from the dimensions of the acetabulum may result in a relative undersizing of the femoral component.6 By contrast, estimation of the size from the diameter of the femoral head may give relative oversizing of the acetabular component and removal of relatively more acetabular bone.

Resurfacing acetabular components all have an articular arc which is the angle subtended by the articular surface, and is less than a hemisphere (180°) (Fig. 3). Most are thicker at the apex than at the periphery. The inner articular surface is not concentric with the outer surface since the centre of rotation is offset resulting in a smaller articular arc. Furthermore, detail inside the margin of the acetabular component such as small chamfers or grooves for attachment of the inserter can further reduce the articular arc. The latter ranges from 170° down to as low as 144° (Fig. 4). While a smaller articular arc may increase the range of movement before impingement, it also increases the risk of edge-loading, especially if there is any malpositioning of the acetabular component.

The femoral component has a short central stem, the primary function of which is to allow its accurate insertion. Isaac et al5 proposed that for an optimal design this stem should be proportional to the size of the component. This would minimise stress-shielding within the femoral head and the amount of bone removed for its insertion. Unfortunately, with many current designs, the femoral stem is not proportionally sized, with the result that it is relatively thicker in the smaller sizes (Fig. 2).

Loading of the femoral neck
After resurfacing arthroplasty of the hip the presence of the metal femoral component changes the biomechanical environment within the proximal femur most markedly by increasing the strains in the superior aspect of the femoral neck.6-8 This is of particular concern because of the incidence of fracture as a cause of failure after this procedure.9,10

Resurfacing of the femoral head also results in considerable strain-shielding in the superior aspect of the femoral head leading to changes in the bony architecture by strain-mediated remodelling.6-8 The cobalt-chrome alloy stem has a higher modulus of elasticity than the native bone of the femoral head and neck. This results in stress-shielding of the bone adjacent to the implant. Several studies evaluating the effect of orientation of the prosthesis have shown that the presence of the femoral stem results in some degree of stress-shielding within the proximal sections of the femoral head.6-8 Finite-element analysis has indicated that the degree of stress-shielding in the femoral head is further elevated when the thickness of the stem is increased so that it can extend to the femoral head-neck junction,6,8,11 thereby potentially increasing the risk of late fracture of the femoral neck. Therefore alterations in localised stress and strain can be linked to both short- and long-term failure.

Considerations regarding smaller sizes of femoral component
The effects of the smaller implant on stress and strain within the femoral head are similar to those described for the femoral neck.8 If stiffness is expressed as a percentage of the total neck-stem construct it provides a measure of the percentage of stress-shielding. When stem size remains unchanged as the size of the component decreases, as is seen with most resurfacing implants, the stem contributes a greater proportion of the total stiffness and increases the stress-shielding (Fig. 5). In an attempt to reduce stress-shielding, some designs of implant have proportionally thinner stems for components of smaller diameter to mitigate against the mismatch in stiffness between the stem and the bone of the proximal femur.12 However, evidence that this has a positive influence on bone remodelling has not yet been published.

Wear debris
Soluble metal ions or particulate metal debris from wear of metal-on-metal resurfacing arthroplasties of the hip have been associated with reaction to metal debris, metal toxicity, osteolysis and loosening of the component.12-15 The presentation of patients with unexplained pain necessitating revision13 and histopathological analysis of inflammatory tissue adjacent to poorly performing implants, have meant that there is a continued interest in the role of metal wear debris in failures of resurfacing arthroplasties of the hip.14-18

Three types of lubrication regime have been identified for metal-on-metal bearings: 1) boundary lubrication which occurs when there is very close or direct contact between asperities resulting in molecular adhesion of the moving surfaces and high rates of wear; 2) fluid-film lubrication in which the moving components are separated by fluid and results in very low rates of wear; and 3) mixed or elastohydrodynamic lubrication in which there is a combination of boundary lubri-
cation at areas of close contact as well as fluid-film lubrication. The bearings used in resurfacing arthroplasty predominantly have a mixed form of lubrication. Features which optimise the lubrication regime of resurfacing components towards the fluid-film include increasing size of the femoral component and ideal diametric clearance.

Resurfacing components have two phases of wear, namely, ‘running-in’ and ‘steady-state’. The former involves the wearing down of surface asperities which result in a high early rate of wear. After this, steady-state wear is predominant with fluid-film lubrication and results in minimal further wear.

The orientation of the acetabular component has also been shown to influence wear and the levels of metal ions. The abduction angle recommended in the manufacturer’s literature for acetabular components is 45°. However, as a consequence of the reduced articular arc and altered centre-edge angle, the effective inclination angle achieved at the bearing surface for many resurfacing prostheses is greater than this. Steeply inclined components yield higher metal ion concentrations, as a result of edge-loading, which disrupts the fluid-film lubrication and gives a high degree of wear. A similar phenomenon is also seen as a consequence of deformation of the acetabular component during insertion.

Considerations regarding the size of the femoral component. The lubrication theory is central to the prediction of the wear behaviour of large metal-on-metal bearings. An increase in the size of the component is thought to be beneficial to lubrication because of an increase in sliding velocity which enhances fluid-film lubrication. When the hydrodynamic regime is maintained, the rate of steady-state wear debris does not differ significantly with head
size, but since large head sizes progress from bedding-in to steady-state wear at an earlier stage, an overall decrease in volumetric wear ensues. This evaluation is supported by a recent study which found an increase in the concentration of chromium and cobalt ions in the whole blood of patients with smaller (51 mm or less) femoral components than in those with larger (53 mm or greater) components.

In addition to the increase in volumetric wear from the smaller components, there is also an increased risk of edge-loading in smaller components because of the design feature which lateralises the centre of rotation and reduces the articular arc. In small components there is a reduced distance between the load vector and the edge of the bearing surface which increases the risk of edge-related wear leading to higher levels of metal ion generation in some cases. Other factors contributing to edge-loading wear include the orientation of the component and the range of hip movement.

Penetration of cement

The role of cement in the failure of an implant and the need for revision has been studied. Analysis of excised femoral heads found that the cement mantle and depth of penetration vary widely, depending on the viscosity of the cement, the bone density and the design clearance between the reamed head and the femoral component. Experimental evidence supports the possibility of thermal necrosis in the prepared femoral head associated with resurfacing. In addition, infiltration of cement and cementing of the stem can increase stress-associated changes resulting in increased stress-shielding in the femoral head and stress-loading of the femoral neck.
Considerations regarding a smaller head size of femoral component. Krause, Krug and Miller\textsuperscript{38} showed that the penetration of cement increases with increased pressure of application. Measurement of the impaction load during insertion of resurfacing components showed forces as high as 20 N to be present, potentially predisposing the underlying bone to fracture.\textsuperscript{39} If the same pressure was applied during implantation of the femoral component regardless of the size of the femoral head, a greater load per unit area could be expected with smaller heads, and, accordingly, the possibility of deeper penetration of cement. Another factor which increases the penetration of cement markedly is a low bone mineral density (BMD).\textsuperscript{40,41} This is found more often in women. In addition, women generally receive smaller components and have been shown to have an elevated risk of revision.\textsuperscript{1} Given that the penetration of cement is proportional to pore diameter and the square root of the pressure applied to the cement,\textsuperscript{41} the combination of a small size of femoral head and a low BMD could theoretically result in excessive penetration of cement with some small components.

Orientation of the component
The correct anatomical alignment of components is important in resurfacing arthroplasty of the hip, even more so than for total hip replacement. Malpositioning of the femoral component can be identified on post-operative radiographs. However, the accurate assessment of acetabular position using plain radiography is difficult because of partial concealment by the femoral component. It has been reported recently that 64\% of revisions are performed because of malpositioning of the acetabular component.\textsuperscript{12}

It has been described previously that steeply-inclined acetabular components result in higher serum concentrations of metal ions.\textsuperscript{21} This finding is further compounded when prostheses with a small arc of cover are used. De Haan et al\textsuperscript{21} found that implants with cover of < 10 mm had an 18\% chance of very high wear, which was reduced to 0.6\% in implants with cover of > 10 mm.

A small amount of varus malpositioning of the femoral component can produce enough load to induce fracture in patients with normal BMD.\textsuperscript{42,43} A study by Ong et al\textsuperscript{6} showed the potential for varus malpositioning to increase strain energy around the mid-stem and at the mouth of the femoral component, thus potentially increasing the risk of fracture. Positioning of the femoral component into at least 10\dgr of valgus results in more physiological stresses within the femoral neck, but excessive valgus malpositioning may produce notching of the femoral neck and an increase in the risk of fracture.\textsuperscript{44}
Considerations regarding the size of the component. Larger acetabular components are more tolerant of the effects of malalignment in abduction and version and more forgiving with respect to impingement, microseparation, edge-loading, rim damage and subluxation than smaller components which have an accompanying smaller articular arc.\(^4\)\(^,\)\(^2\) An acetabular component with a radiological inclination of 45° will have an effective inclination angle (δ) of between 50° and 63° depending on the type and size of the component\(^4\) (Figs 3 and 6). Therefore reduction of the inclination angle of the acetabular component is particularly important for smaller components to avoid adverse consequences such as edge-loading.\(^4\)

The incorrect orientation of the femoral component during insertion is recognised as a cause of notching of the femoral neck which is undesirable because of its reported association with neck fracture and damage to the blood supply of the femoral head.\(^9\)\(^,\)\(^4\) It has been suggested that undersizing of the femoral component occurs not infrequently when using digital pre-operative templating which increases the likelihood of notching.\(^4\) In a study on composite femora a notch of 5 mm weakened the femur by 47% whereas that of 2 mm weakened it by 24%.\(^4\) From this it can be extrapolated that a notch of 2 mm in a patient receiving a femoral component of 38 mm is relatively more serious than in a patient receiving a component of 55 mm. Accordingly, smaller patients are at greater risk of the consequences of femoral notching.\(^4\)

Vascularity of the femoral head

Johnson, Soultanis and Soucacos\(^4\) have described in detail the nature of the intra- and extra-osseous blood supply to the normal adult femoral head, which is helpful in understanding the possibility of vascular damage which may occur during resurfacing arthroplasty. The extraosseous supply is of particular interest because of its vulnerability during resurfacing. The surgical approach and preparation of the femoral head during reaming\(^39\) can decrease blood flow and oxygen concentration within the femoral head.\(^50\)\(^-\)\(^53\) While the relevance of vascular injury remains controversial, it has been linked to narrowing of the femoral neck, femoral fracture and late loosening of the femoral component.\(^9\)\(^,\)\(^4\)

Studies measuring the blood flow to the femoral head when using a posterior approach commonly report a decrease ranging from 40% to 70% and, more rarely, complete cessation.\(^30\)\(^-\)\(^32\) In addition to the decrease in blood flow during the surgical approach, Beaule et al\(^4\) have shown that notching of osteoarthritic femoral heads can reduce blood flow by 50% or more.

Several studies\(^4\)\(^,\)\(^51\)\(^,\)\(^53\) have shown that disruption of the extraosseous blood supply results in some reduction in the blood flow, but the influence of this on the formation of osteonecrosis remains unproven. Separate studies on retrieved femoral heads have failed to provide gross evidence of avascular necrosis (AVN) which could be attributable to disruption of the extraosseous blood supply. One study showed that loosening commonly occurred in the absence of AVN, and proposed that loosening may be related to local increases in pressure, abrasion by cement and interference with the local blood supply.\(^54\) This is further supported by the results of Campbell, Mirra and Amstutz\(^55\) which suggested that resurfacing did not result in generalised AVN, but instead produced localised osteonecrosis from thermal necrosis.

An explanation of these findings may lie in the variability in vascularisation through the retinacular vessels\(^56\) and in the presence of an intraosseous blood supply. Whiteside et al\(^57\) have shown that the dependency of the blood supply to the femoral head on the retinacular vessels decreases during the development of osteoarthritis because of the formation of abundant vascular anastomoses between the epiphysis and the metaphysis. Retrieved human femoral heads showed similar findings\(^58\)\(^,\)\(^59\) which calls into question the relevance of insufficient blood flow as a cause of osteonecrosis and implant failure.

Considerations regarding the size of the femoral head. The role of vascular damage in relation to the size of the femoral head is uncertain partly because of conflicting evidence in the literature and partly because the size of the head is seldom a factor investigated in studies on its head vascularity. Although more evidence is required before accurate conclusions can be drawn on any relationship between a small femoral head, vascular damage and failure of resurfacing, it may be reasonable to postulate that: 1) there is a reduction in the amount of remaining intraosseous bone because of the presence of the relatively larger stem in the small component sizes in the principal brands; and 2) the amplification effect of surgical error in notching is greater with smaller components.

For smaller patients there is the potential for relatively greater damage to the intraosseous blood supply during insertion of the femoral stem. Steffen et al\(^53\) showed that insertion of the femoral component decreased the oxygen concentration by a further 20% in addition to any decrease observed during the surgical approach. The relatively greater size of the stem in small patients may produce more damage to the intraosseous blood supply than in larger patients.

Beaule et al\(^4\) showed that a simulated notch created using an osteotome of 0.75 inches resulted in variable decreases in blood flow to the femoral head. A possible explanation is that the notch was proportionally larger in patients with a smaller femoral head, and consequently resulted in greater damage to the blood supply. Unfortunately, the effect of the size of the femoral head was not reported.

Conclusions

Failure of resurfacing arthroplasty of the hip is likely to be multifactorial, and many authors have alluded to some of the contributing factors. The issue of head size has recently been highlighted in the Australian Joint Replacement Reg-
The study of failed resurfacing arthroplasties requiring revision is made somewhat easier because the femoral heads are excised and are thus available for analysis. However, it appears that many different causes of failure promote similar pathological changes in vivo, making identification of the primary cause of failure difficult. Some clinical studies account for the size of the component in their design, but do not appear to test for a relationship with outcome. The future designs of pathological, clinical or experimental studies which allow the effect of the size of the component to be tested, may help to better define patient implant- and surgeon-related risk factors for resurfacing arthroplasty of the hip.

Our review has explored how some of the factors which are possibly related to failure may be influenced by the size of the component. It is clear that these factors do not have an equal influence on the outcome of resurfacing arthroplasty. The inter-relationship between them makes it difficult to identify which are the most important in causing failure in small components. Having stated this, we believe that the two most influential are the design and geometry of the components and the orientation particularly of the acetabular component since each is associated with different modes of failure and modification of either may improve the outcome of resurfacing arthroplasty of the hip.

Supplementary material

Details regarding the calculation of the bending stiffness of a beam with the relevant references are available on our website at www.jbjs.org.uk

We wish to thank A. Pearce, Dr R. Campbell and M. Gillies for their assistance with the preparation of the manuscript.

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

References


