(i) Head size, does it matter?

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Summary
Femoral head size remains one of the most controversial and oft debated aspects of hip replacement surgery. Sir John Charnley set the debate in motion in his paper on Low Friction Arthroplasty with the emphasis on finding the ideal head size to reduce friction and therefore, it was thought, wear. As our understanding of tribology improved and with the development of more wear-resistant materials, the emphasis has shifted towards finding the ideal size to improve joint stability. The ability to use large diameter heads has provided an opportunity to expand the indications for total hip arthroplasty to include trauma and younger patients.

Introduction
Sir John Charnley introduced his Low Friction Arthroplasty in 1962. Prior to this large head metal-on-metal implants (such as those designed by Kenneth McKee and Peter Ring) were used but with mixed results. Originally Charnley used Teflon sockets to minimise friction but this was not successful due to rapid wear. Once High Density Polyethylene (HDPE) was introduced it became apparent that outcomes improved when as small a head as possible (that would cope with load transmission) was used. This had the effect of both reducing the frictional torque on the acetabulum at the cement-bone interface and increasing the available thickness of the socket thus improving its protection against linear wear. He determined that in order to maximise the time taken for complete penetration of cup by the head, the ideal head diameter was approximately half the outside diameter of the cup. Thus the 22.25 mm diameter head was launched used with, usually, a 40 or 43 mm cup. It has subsequently been shown that larger heads increase the volume of HDPE wear debris produced (Fig. 1).

Total hip arthroplasty was not widely adopted in the UK for the elderly with intracapsular fractures because of what was perceived to be an unacceptably high dislocation rate with small heads compared with conventional hemiarthroplasty (20% compared to 13% respectively). It was felt that the non-diseased, previously active hip, combined with the lack of compliance by this particular population contributed towards this increased risk and the large head hemiarthroplasties thus had the advantage of being more stable as well as cheaper.

With dislocation rates for total hip replacement usually quoted as 1 to 5% for primary arthroplasty and as high as 16% for revision arthroplasty, the use of small heads has been challenged in an attempt to combat this dislocation risk.

Two main issues have therefore evolved over the determination of the ideal head size: Wear and Stability.

Effect on wear
Wear is defined as the erosion of material from a solid surface by the action of another surface. The volume of...
material eroded can be calculated using the Archard Equation:

\[ W = K \times \frac{L \times d}{H} \]

- \( W \) = volume of wear
- \( K \) = constant depending on the surface properties of the materials
- \( L \) = normal load
- \( d \) = sliding distance
- \( H \) = hardness of the softer material

From this it is seen that the greater the sliding distance the more wear particles are liberated. It implies that the smaller the head diameter, the smaller the circumference and thus sliding distance, hence less wear. However, this is a simplistic approach as there are other factors that affect the constant \( K \), including the area over which the abrasive particles are spread. The smaller this area, the more the harder surface can penetrate into the softer material producing linear (or penetrative) wear.

Livermore described a technique for measuring this linear wear (Fig. 2) and although newer methods using 3-dimensional analysis and digital edge detection have been described, Livermore’s method remains the gold standard.4

Theoretically, therefore, the large diameter produces higher volumetric wear, but less penetrative wear. There must, however, be an ideal size that produces the least amount of both volumetric wear and penetration in vivo. Livermore looked at three different size heads (22 mm, 28 mm and 32 mm) in 385 hips over 9.5 years and demonstrated that 28 mm heads produced significantly less linear wear in polyethylene cups than the other two sizes. He also demonstrated that 32 mm heads produced the highest volumetric wear but there was no significant difference in volumetric wear between the 22 and 28 mm heads. He therefore advocated the use of 28 mm heads as the best compromise between linear and volumetric wear given that the volume of debris is of paramount importance in initiating the biological reactions which lead to osteolysis (Fig. 3).

The two main criticisms of this paper are that, first, only antero-posterior radiographs were used without taking into account patient positioning and second, the calculation for volumetric wear was made assuming that the wear pattern is a simple cylinder with a radius equal to the radius of the head. This has been shown to overestimate the true value, particularly as plastic deformation and creep were not taken into account.5 Kabo et al. looked at the relationship between wear and head sizes, ranging from 22 mm to 54 mm, for retrieved conventional and resurfacing arthroplasties and found that linear wear actually increased with head size and concluded that this was due to the reduced thickness of the cup.6 A typical instance of failure is shown in Fig. 4.

In short, to reduce wear in metal on polyethylene articulations, ‘Petite is preferred’.

**Effect on stability**

**Implant stability: frictional torque on the cup**

Charnley first described his ‘Low Friction Arthroplasty’ as having reduced torque on the acetabular cement-bone interface. The calculation of frictional force (F) at this interface is demonstrated in Fig. 5.

\[ F = \mu LR_1 / R_2 \]

- \( \mu \) = coefficient of friction
- \( L \) = normal load
- \( R_1 \) = internal diameter of the cup
- \( R_2 \) = outer diameter of the cup at the bone-cement interface
As the diameter of the head increases and thus the ratio of inner to outer diameters of the cup proportionately, the frictional torque produced at the bone-cement interface also increases. However, although this has been shown in vitro, it was felt that the frictional moments would not be large enough to cause any clinical loosening. This, however, has been disputed by Morrey et al. who looked at 6128 total hip arthroplasties over 9 years and found a higher incidence of acetabular loosening amongst those with 32 mm heads compared with those with 22 mm heads. It could be argued, though, that the loosening was in fact due to increased volumetric wear and not the increased frictional force.

**Joint stability**

Despite advances in hip arthroplasty technology and techniques, dislocation remains a troublesome complication, second in frequency only to late aseptic prosthetic loosening. Although factors such as operative approach, component positioning, patient age, sex and cognition are risk factors, the size of the femoral component head affects the dislocation risk because of the following variables:

- Primary Arc Range
- Excursion Distance

The Primary Arc Range (PAR) is the arc the ball can articulate within the socket before impinging and levering
out. This is determined by the Head:Neck ratio. The larger the head diameter compared with the neck diameter, the greater the arc. By altering the neck taper design as well as using the largest possible head diameter, arc range can be increased quite dramatically (Fig. 6).

Modifying the rim of the cup can further influence the primary arc (Fig. 6).

The Excursion Distance is the distance the head must travel in order to dislocate once the neck begins to impinge. If the cup encloses the head by $180^\circ$ a 22 mm diameter head will have to travel 11 mm to dislocate. Likewise, a 44 mm diameter head will have to travel 22 mm (Fig. 8)

Any modification to the cup rim can affect this excursion distance.

The most stable implant, therefore, has a cup which allows a sufficient arc range (without sacrificing the excursion distance) and a large head with a small neck that is able to withstand the load and is tapered in such a way as to further increase the arc range. There is, however, no substitution for correct placement of the implants as this ensures that the designed arc range remains within the patient’s functional range of motion.

There have been many anatomical studies demonstrating how the use of larger heads reduces the dislocation rate. However, the situation is more complex in vivo. Kung et al. looked at the dislocation rate in 230 revision hip replacements, splitting them into 4 groups. Group 1 had 22 mm heads with intact abductor mechanisms. Group 2 had 22 mm heads with absent abductor mechanisms. Group 3 had 36 mm heads with intact abductors and Group 4 had 36 mm heads with absent abductors. They found that although the dislocation rate improved using 36 mm heads in the group with intact abductors, there was no improvement if the abductors were absent. It is possible, therefore, that with poor abductor function, size really does not matter. Amstutz and Reed both demonstrated another interesting point in their cadaveric studies. They showed that with a head diameter of over 28 mm, neck impingement on the cup no longer becomes an issue as the trochanter tends to impinge against the pelvis first. Thus they concluded that there was no extra benefit to be gained by using a 32 mm head over a 28 mm head in terms of dislocation.

A recent analysis of the Norwegian Hip Registry by Bystrom et al., however, appears to contradict this finding. They studied the risk factors that lead to revision for prosthetic dislocation. 42 987 primary hips were examined and it was concluded that the femoral head size was an important risk factor. It was shown that overall, 28 mm heads were four times more likely to require revisions than 32 mm heads. This was particularly so in the older age groups. An analysis of just the Exeter implants showed an increased revision rate with 26 mm heads compared with 32 mm heads. Interestingly, the Charnley 22 mm heads had a lower revision rate than the Exeter 26 mm heads and an equivalent rate to the Exeter 28 mm heads. This would
indicate that head size is not the sole contributing design factor towards revision for dislocation. The authors acknowledged that the limitation of their study was that they were using revision surgery for dislocation as the end-point and thus excluded the large proportion of patients who did not have revisions despite dislocations. Nevertheless, it appears that to improve joint stability, ‘Bigger is better’.

Practice points
- Initial concerns about frictional torque and polyethylene wear limited the head size
- Larger diameter heads improve the excursion distance
- Greater Head:Neck Ratios improve the Primary Arc Range
- With very large heads, the limiting factor is bony impingement

Further developments

Traditionally, head size was limited by the concerns about wear and frictional torque on the acetabulum. Although this may be relevant for Ultra High Molecular Weight Polyethylene, it may not be so with newer, harder wearing materials. Improvements in technology have led to the development of four alternative articulations:

- Ceramic on Ceramic
- Metal on Metal
- Metal or Ceramic on Highly Cross Linked Polyethylene
- Surface treated Metal Alloy Heads on Polyethylene

(The advantages and disadvantages are summarised in Table 1).

Ceramic on ceramic

The use of ceramics (Alumina) as a replacement for joints was first proposed by Rock in 1930. However, it was not until 1965 that Sandhaus patented an alumina material, known as Degussit AL 23, for hip joints. Zirconia was later developed in the 1970s. Since then improvements in manufacturing technology have resulted in superior purity, grain size, strength, surface properties and fracture mechanical properties. Modern implants have a surface roughness as low as 0.002 microns. To illustrate this, if a zirconia 32 mm ball was scaled to the same size as the Earth, the average roughness would be only 0.7 m! The result is excellent wear characteristics, with in vitro rates as low as 0.007 mm³/million cycles, compared with Cobalt Chrome on Poly rates of 70–90 mm³/million cycles.16

Logically, if wear was no longer an issue, it would make sense to use very large heads, particularly as dislocation can be catastrophic owing to the brittle nature of ceramics. At the International BIOLOX® Symposium in 2007, Karl-Heinz Widmer suggested that although an increase in head diameter equated to improved joint stability, the relationship was not linear and a reasonable threshold for maximum head size would be 44 mm. However, ceramic heads used in ceramic-on-ceramic articulations have not been available in such large diameters. This is largely due to limitations of their mechanical properties as larger heads require thinner cup liners. The strength of a material is its ability to withstand stress. Zirconia is a stronger material than alumina and so it can be made thinner. However, zirconia is not as hard as alumina and therefore has a higher wear rate and therefore a ceramic-on-ceramic combination is not possible with zirconia. Furthermore, after an unexpectedly high rate of fractures of zirconia femoral heads from a single manufacturer, there was a worldwide recall of zirconia heads in 2001. Manufacturers have subsequently developed a composite known as Zirconia-Toughened Alumina (ZTA) which provides a combination of improved material strength with only a small degradation in hardness compared to alumina, so allowing thinner cups and thus larger heads. Currently, the largest ceramic heads available

### Table 1

<table>
<thead>
<tr>
<th>Bearing</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Max head size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic/ceramic</td>
<td>Very low friction, very low wear Biointert</td>
<td>Head size limited by cup thickness</td>
<td>36 mm</td>
</tr>
<tr>
<td>Metal/metal</td>
<td>Fluid-film lubrication produces very low wear rates, wear actually reduces with increased diameters Head size is not limited by cup thickness</td>
<td>Unknown long-term effects of raised metal ion concentrations</td>
<td>Limited only by patient size</td>
</tr>
<tr>
<td>HXL Polyethylene</td>
<td>Can be made thinner than conventional poly thus allowing larger head sizes</td>
<td>Fears of surface delamination, pitting and cracking</td>
<td>40 mm</td>
</tr>
<tr>
<td>Surface treated metal heads</td>
<td>Low friction of ceramic with ductility of metals</td>
<td>Can only be used with poly cups Dislocation can cause severe damage to the heads</td>
<td>44 mm</td>
</tr>
</tbody>
</table>
on the market are 36 mm, with a minimum metal backed cup size of 50–52 mm. With these new composite materials and improved machining, wall thicknesses of only 2.5 mm of liner and cup are now possible. As the ability to make thinner metal shells improves, head diameters of 40 to 44 mm could theoretically be manufactured with cup outer diameters of 52 to 60 mm. With further advances and innovations in acetabular component technology, we may witness even larger ceramic head sizes in the future.

### Metal on metal

Like ceramics, the idea of metal-on-metal articulations is not new. Philip Wiles used the first metal-on-metal (stainless steel) articulation in 1938. His registrar, McKee, modified the device in the 1950’s with Cobalt Chrome Molybdenum. Watson Farrar further developed it by improving the Head:Neck ratio. Peter Ring in 1964 developed his metal-on-metal prosthesis to fit a standard 40 mm Moore prosthesis. D’Aubigné used head sizes of 35 mm and 41 mm. Metal-on-metal implants thus allowed the use of large heads and Müller designed a metal-on-metal resurfacing prosthesis in 1967.

The McKee-Farrar replacements were very popular in the 1960’s, but by the mid-1970’s, they were largely abandoned. The reason was probably a combination of the consistent success of Charnley’s Low Friction Arthroplasty, high infection rates and concerns with metal sensitivity. The success rate was very variable with poorer survival figures than the Charnley implant at 5 to 15 years, but curiously, much better rates at 20 years and beyond. Interest in metal articulations was thus renewed in the 1990s with the emphasis on finding the reason for these late successes. In 1996 Schmalzried reviewed patients with successful McKee-Farrar implants and noted that implant positioning and patient stature had a great influence on longevity. Many laboratory studies demonstrated wear rates that were initially high, but later dropped after a ‘wear-in period’. However, a key discovery to the success of some implants over others was the understanding of ‘clearance’. This is the difference in radius between the two surfaces. Semlitsch performed a retrieval study on 42 mm head metal-on-metal articulations and found, for that diameter, the lowest wear rate occurred when the clearance was in the range 0.06–0.1 mm. This difference produced the lowest contact stress. A smaller clearance, which was deliberately attempted in some of the older implants to produce an ‘exact fit’, actually resulted in increased loosening because of seizure of the surfaces due to cold welding at the equators. Thus it is beneficial to create a controlled clearance to generate a POLAR contact as opposed to EQUATORIAL contact (Fig. 9).

The ideal clearance varies for different radii heads and is influenced by many factors that are beyond the scope of this article. Nevertheless, an understanding of the ideal dimensions and the technology available to achieve these tolerances can lead to very low wear rates. Modern metal-on-metal articulations have linear wear rates 40 times lower and volumetric wear rates 200 times lower than metal-on-polyethylene articulations. It appears that wear rates actually decrease with larger diameter heads provided the correct clearance is achieved. This appears to contradict the earlier rationalisation that an increased radius results in an increased sliding distance and thus an increase in volumetric wear. The reason lies in the type of lubrication observed in this articulation. McNie and Dawson demonstrated evidence of fluid-film lubrication between the metal surfaces. Simply put, this uses a thin film of lubricant to separate the asperities of the bearing surfaces and thus reduce the coefficient of friction by one or two orders of magnitude. The reality is probably that the articulations experience a mixture between fluid film and boundary lubrication (Fig. 10).

With wear actually decreasing as well as joint stability increasing with head size, it is clearly advantageous to make metal-on-metal head sizes as large as possible. Furthermore, as metal cups can be manufactured relatively thin, there is less limitation on size compared with the other materials.

The current main contributing factor to the reluctance by many to adopt metal-on-metal prostheses is the concern about metal sensitivity, teratogenesis and carcinogenesis. Although the local consequence of bone resorption resulting from metal particles appears to be less important than that produced by polyethylene debris, there is a significant increase in serum ion levels of the component metals. It is the unknown effects of this that causes concern.

Visuri analysed the risk of cancer in patients with metal-on-metal (McKee-Farrar) hip replacements followed-up over 30 years. He looked at a range of cancers and concluded that the incidence of leukaemia was significantly increased over the expected rate during the 5 to 14-year follow-up period. He also found a significant increase in cancers of unknown site amongst females. Interestingly, however, he noted a slight decrease in the incidence of lung and urological tract cancers. Overall, Visuri felt there was no long-term difference in cancer risk from the general population.

Fears of teratogenicity have developed from animal studies showing developmental toxicity from administering metals to mammals. Laboratory experiments have also demonstrated the possibility of DNA damage. However, Ziaee and McMinn et al. showed that the human placenta has a complex modulatory effect on the transfer of Cobalt...
and Chromium ions to the foetus and concluded that at high levels such as seen in patients with metal-on-metal implants, the placenta prevents excessive transfer so that the foetal levels are maintained at the normal baseline.\textsuperscript{24} Perhaps we should also look at the effects of ions on male spermatogenesis?

There have been reports of local lymphocytic infiltration (ALVAL) that have also caused concern. However, as yet there does not appear to be any correlation between this observed phenomenon and clinical failure or requirements for revision. However, there is evidence accumulating that revision rates for metal-on-metal bearings are higher in the smaller bearing sizes.

Although the long-term effects of metal-on-metal articulations remain unknown, the ability to use very large heads with little wear remains very appealing.

Highly Cross-linked Polyethylene

Highly Cross-linked (HXL) Polyethylene was originally developed to address the poor wear properties of polyethylene compared with other materials. By improving the strength of the material, the amount of particle formation and thus wear is reduced. It was noted that strong cross-linking bonds were formed during the irradiation process. The higher the dose of radiation, the more the number of cross-links formed. Free radicals are formed as a by-product, which oxidise over time and degrade the material. By heat-treating the irradiated polyethylene, the free radicals are destroyed, thus preventing further oxidation (Fig. 11). The heat used can be either above the melting point of the polymer or below (annealing) and different manufacturers argue one’s superiority over the other. Nevertheless, the improved strength can allow the manufacture of thinner liners and thus larger heads. Furthermore, studies have shown that head size has no significant effect on the wear rates of highly cross-linked polyethylene.\textsuperscript{25} Engh showed a wear rate reduction of 95\% compared to standard polyethylene at 5.5 years follow-up.\textsuperscript{26}

Highly cross-linked polyethylene can be used with either ceramic or metal heads. Using a hip simulator Fisher compared 36 mm ceramic and cobalt chrome heads articulating against HXL polyethylene and demonstrated a 50\% decrease in wear rate but also showed an increase in initial creep of the cups with ceramic heads.\textsuperscript{27}

Not all share this optimism for HXL polyethylene. Bradford showed that highly cross-linked polyethylene cups were failing not from wear but from surface delamination, cracking and pitting.\textsuperscript{28} The future will hold the answer.

Practice points

- Fluid film lubrication is the key to low wear rates in metal-on-metal bearings
- Metal-on-metal bearings require controlled clearance to allow fluid film lubrication
- With the correct clearance, wear rates reduce with larger diameter heads
- Concerns of metal sensitivity, teratogenesis and carcinogenesis remain but are not proven

Surface treated metal alloy heads

Manufacturers have developed metal alloys that are treated to produce a ceramic surface, such as Zirconium Oxide, in an attempt to combine the advantages of ceramic hardness and metallic ductility. There is an integrated gradient under the surface thus preventing this ceramic surface from delaminating. However, the major disadvantage is that the cups must be made of polyethylene. The issues of head size are thus still limited by the drawbacks of polyethylene cups, although the manufacturers claim to have shown a 45\% reduction in wear compared to cobalt-chrome heads on standard polyethylene cups in in vitro hip-simulator studies.

In the event of dislocation, oxidised surface heads, which tend to be much softer than the metal shells usually used in cups, have been shown to sustain very deep scratches. It is therefore recommended that dislocations with these implants be reduced open and/or followed-up carefully.\textsuperscript{29}

An alternative surface treatment is the use of Nitrogen ion-bombarded cobalt-chrome. As with the oxidised zirconium...
alloy, the result is an integrated sub-surface gradient, which does not delaminate. The advantage of this surface is that it greatly reduces the coefficient of friction. Maruyama performed a matched case-control study on patients with and without these treated femoral heads and demonstrated a significant reduction (28%) in wear using standard polyethylene cups, particularly in patients younger than 60. The current head sizes available for ion-bombarded metal are 22 to 44 mm (40 to 44 mm heads are only compatible with highly cross-linked polyethylene).

**Fractured neck of femur**

Former reluctance to use Total Hip Arthroplasty in elderly patients with intra-capsular fractures was largely based on fears of high dislocation rates. However, with new technology and materials allowing larger head sizes, joint stability should be less of an issue and financial factors may be of more importance. With an ever-expanding elderly population, this financial burden cannot be ignored. However, with functionally active, more compliant patients, total hip replacement has been shown to provide better functional outcomes and longer implant survival compared to hemiarthroplasty. It is in these patients that a large head total arthroplasty may be beneficial.

**Recurrent dislocations**

The treatment of recurrent dislocations following total hip arthroplasty can be challenging, particularly if it is secondary to a poor soft tissue envelope. Traditionally, methods of increasing the excursion distance with Posterior Lip Augmentation Devices or Constrained Liners are used for this problem. However, this greatly reduces the available primary arc range, which can lead to increased stresses at the non-articular interfaces. An alternative solution would be to use the larger head sizes available, thus improving both excursion distance and arc range. Amstutz et al. looked at implants with an average head diameter of 44 mm used for revising recurrent dislocating prostheses. They used the term ‘Jumbo Head’ for head sizes above 39 mm. Although they only looked at 12 hips, all but one had no further dislocations over an average follow-up of 6.5 years. It important to note that nine of these patients also had reorientation of the acetabular components, which may also have contributed to improved stability.

**Larger ceramic heads for ceramic-on-ceramic bearings**

The advantages of biocompatibility and very low wear rates with ceramics are clear. Ceramic head sizes are limited by the minimum thickness requirements of the modular ceramic lined metal shelled cups. The following are three approaches that are being researched to counteract this limitation:

1. Ceramic-on-metal articulations
2. Ceramic-metal monoblock cups
3. Monolithic ceramic cups

**Ceramic-on-metal articulations**

Traditionally, the choice of implant was a compromise between wear rates and joint stability. Ceramics have very low friction and wear rates. Metals can be manufactured into thin cups, thus allowing larger heads and greater stability. The combination should therefore obviate the need to
compromise. In-vitro studies have demonstrated wear rates as much as 100 fold lower than metal-on-metal articulations. Manufacturers are thus developing such systems with additional claims of improved fluid film lubrication, reduced corrosive wear and reduced metal ion levels. Diameters of up to 44 mm have been developed.

Ceramic-metal monoblock cups

Another method of keeping the cup thickness to a maximum is to use monoblock cups. Instead of relying on a taper-fit mechanism between the ceramic liner and metal shell, the cup is manufactured as one piece. Manufacturers believe that head diameters up to 48 mm can be achieved with this method. One of the challenges is to provide a robust method of insertion and fixation, which does not rely on cup deformation and elastic recoil.

Monolithic ceramic cups

The final method of keeping the cup thick is to directly attach the ceramic to the bone without the need for an additional metal interface. Manufacturers are developing ceramic cups with an osteoinductive outer surface to allow direct bone ongrowth. Although very much in its infancy, researchers have developed cups that have successfully integrated into mammalian acetabula. The mechanical properties of such implants have yet to be determined.

Conclusions

It is important to weigh the risk of dislocation against the wear rate when deciding on head size. In the elderly, wear may not be as much of a concern. Indeed dislocation appears to be marginally more affected by head size in the elderly than in the young. In the young, wear is more of a problem and one solution may be to use smaller head sizes with conventional polyethylene cups. However with increasingly active, higher demand patients, the use of materials that reduce the amount of wear without having to sacrifice head diameter and thus joint stability is a more appealing solution. Head size still matters but as materials improve, it is more the range of motion that counts and less the wear rate. There are exciting developments afoot that may well lead to the evidence presented in this review being rendered obsolete in the future. However, one fact remains, that is accurate insertion and placement of the components is still of paramount importance.

References


Research directions

- Clinical results of large head arthroplasties for trauma
- Novel ceramic cups to allow greater ceramic head sizes
- In-vivo studies of ceramic-on-metal articulations to determine the clinical benefit.