Bioengineering reasons for the failure of metal-on-metal hip prostheses

AN ENGINEER’S PERSPECTIVE

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Clinical experience of metal-on-metal (MoM) bearings in hip prostheses, and in particular in surface replacements, has been disappointing in some series with higher than expected failure rates, which have also been reported in some joint registries. This increased rate of failure is multifactorial, and much has been written recently from a clinical or radiological perspective. This short paper provides an engineer’s view of the biomechanical reasons for the increased rate of wear in MoM bearings, which can lead to increased production of metal ions, adverse tissue reactions and failure. In order to understand the conditions that produce increased wear, it is necessary to define the tribological mechanisms that generate low wear in MoM bearings, and to identify the conditions under which these might break down.

Tribological mechanisms that produce low wear in metal-on-metal bearings

Low wear in MoM bearings has been defined as a wear rate of < 1 mm³ per million cycles. This is associated with a combined serum metal ion level of < 10 parts per billion (ppb), or an individual metal ion level of < 5 ppb in vivo. Under these circumstances, the metal particles generated are mostly of nanometre size in diameter and readily transported away from peri-prosthetic tissue. This transport mechanism can be effective in preventing the build-up of high concentrations of particles around the prosthesis.

In order for these conditions to be achieved, the centre of the femoral head must be concentric with the centre of the acetabular component and the implants correctly positioned. The MoM bearings then operate under a mixed lubrication regime: part of the load is carried by the lubricating synovial fluid and part as a result of contact between the solid metal bearing surfaces. The result is low wear. The proteins in the lubricant also form a boundary layer on the surface of the bearing, which reduces both friction and wear and inhibits the release of corrosion products. After an initial bedding-in period, the bearing surfaces conform better, the contact stresses are reduced, and the protective protein boundary layer is fully formed and stabilised, with the steady-state wear of the metal bearing dropping to well below 1 mm³ per million cycles.

The diameter of the bearing influences these low wear conditions. A 36 mm bearing has a lower steady-state rate of wear than a 28 mm bearing. However, for sizes > 36 mm there is little difference in steady-state wear. A larger-diameter bearing has lower bedding-in wear than a smaller-diameter bearing because of better initial conformity. A smaller clearance between the head and the acetabular component produces a bearing that conforms better and reduces the initial bedding wear, but has little effect on steady-state wear. It is preferable to use a high-carbon alloy, with cast, wrought or heat-treated variants of high-carbon alloys, all of which produce low wear under standard conditions. Much has been written about the tribology, friction, lubrication and wear of MoM bearings under these standard low wearing conditions, which produce wear rates in the range 0.1 mm³ to 1 mm³ per million cycles. It is not necessary to cite...
This material in detail other than to say that failure of these mechanisms can result in rates of wear that are increased by between ten and 100 times. In clinical practice, low wear conditions are present in more than 85% of patients, who typically have low individual metal ion levels (< 5 ppb, or combined metal ion levels of < 10 ppb). We understand much less about increased wear under adverse conditions, which produces elevated metal ion levels and clinical failure, which is the primary focus of this review.

**Adverse conditions that produce ‘head-acetabular component rim contact’ and increased wear**

The low wear conditions described above are generated by MoM prostheses only when the centre of the femoral head and acetabular component are positioned concentrically, with the acetabular component correctly orientated in relation to the biomechanical axis of loading and the contact patch (defined as the area of contact between the head and the acetabular component) and resultant wear occurring within the polished articulating surface of the acetabular component. Deviation from these conditions can result in the tribological contact patch of the head coming into contact with the rim of the acetabular component, producing head-acetabular component rim contact. When this happens wear increases, with stripe wear on the head and rim wear on the acetabular component. The mechanisms of mixed and boundary lubrication that produce low wear in MoM bearings under standard conditions are then disrupted and the wear rate is increased substantially.12-14

There are a number of different conditions that can produce head-acetabular component rim contact (Fig. 1). Both the head and the acetabular components have six independent degrees of freedom, three rotational and three translational. Contact between the head and the rim of the acetabular component can be caused by a number of different sets of conditions. These include:

**Translational malposition:**
- Medial or superior translation of the centre of acetabular component, with failure to restore the acetabular centre, will lead to translational malposition and joint laxity.
- Offset deficiency will similarly fail to restore head centre leading to translational malposition and joint laxity.
- Stem subsidence will result in translational malpositioning of the head with respect to the acetabular component.
- Head-neck impingement will cause levering out of the head on to the rim of the acetabular component.

**Rotational malposition of the acetabular component:**
- Malposition of the acetabular component resulting in excessive inclination will permit its rim to intersect with the tribological contact patch.
- Malposition of the acetabular component in version will also cause its rim to intersect the tribological contact patch.

The significance of head-acetabular component rim contact in hard-on-hard bearings was first seen as stripe wear on the ceramic head in ceramic-on-ceramic bearings,15 being present in more than 50% of retrievals.16 Head-acetabular component rim contact was subsequently shown to increase the wear in MoM bearings and to produce rates of wear well above 1 mm³ per million cycles in laboratory simulators.5,12-14 The first substantial retrieval study of MoM surface replacements also reported head-acetabular component rim contact and increased wear.17 Finite element analysis has shown that a translation of < 0.5 mm (microseparation) can produce head contact on the rim of the acetabular component and head stripe wear and rim wear.18 Translational malposition cannot be seen radiologically, as translations are < 0.5 mm. The rim of the acetabular component acts to constrain the head in an attempt to retain concentricity, but in doing so produces head-acetabular component rim contact, head stripe wear and rim wear.

Rotational malpositioning of the acetabular component, either in inclination or in version, may result in its rim intersecting with the contact patch on the head, permitting head-acetabular component rim contact and cause accelerated wear. The degree of rotational malpositioning which can be tolerated before the rim intersects with the contact.
patch on the head depends on the diameter of the femoral head and the coverage of the acetabular component. A larger-diameter head provides a larger tolerance band for this rotational malposition but the design of the acetabular component has a significant influence on this matter. Acetabular components which are less than hemispherical have a lower tolerance band for rotational malpositioning than fully hemispherical implants.

The degree to which the wear is increased above 1 mm$^3$ per million cycles under adverse conditions and head-rim contact is still not clear. It depends on the conditions and mechanisms that produce this contact, the frequency with which these conditions occur and the design of the component. Different mechanisms of wear occur when the head contacts the rim of the acetabular component as the contact stresses during this contact are increased dramatically. As a result the protective protein boundary layer is removed and mechanical (abrasive and adhesive) wear becomes more prominent and the surfaces rougher. The stripe wear then produced on the head contacts the articulating surface of the acetabular component increasing wear during normal walking. As with ceramic-on-ceramic bearings, there is evidence that head-rim wear in MoM bearings produces larger particles measured in micrometres ($\mu$m) rather than nanometres (nm), and that these may remain in the peri-prosthetic tissues. Simulator studies show that wear rates are increased to between 1 mm$^3$ and 5 mm$^3$ per million cycles with rotational malpositioning and to between 1 mm$^3$ and 10 mm$^3$ per million cycles with translational malpositioning (microseparation), a ten- to 100-fold increase in wear compared with the low steady-state wear rate that occurs under standard walking conditions.

Many factors determine the rate at which wear is increased and to what extent, as a result of contact between the head and acetabular rim. Some of these are more clearly understood than others. Increased wear has been found with a number of alloys (wrought, cast and heat-treated high-carbon alloys), but it is unclear whether this varies according to the alloy in question. Head size has an influence on head-rim contact with larger diameters providing a larger area for the bearing which can better tolerate rotational malalignment. However, if in a larger-diameter acetabular component the angular coverage is reduced as found in some sub-hemispherical implants, this will reduce the tolerance to rotational malalignment and increase the incidence of head-rim contact and the resultant wear. MoM bearings are designed with different gaps between the head and acetabular rim. Some of these are more clearly understood than others. Engineers and researchers need to focus their future research efforts on the effect of adverse conditions on wear. To date, effort has been concentrated on further reducing low wear under ideal conditions, as opposed to reducing the incidence and degree of increased wear under adverse (but realistic) clinical conditions.

**Increased metal wear and ion release from other sources**

The use of larger heads on stems with narrow tapers has increased the risk of corrosive wear at the head-neck taper due to the increased frictional torque that occurs with large-diameter heads and the increased torque on the taper due to head-rim contact. This may contribute to any elevated metal ion levels and adverse tissue reactions. Elevation of metal ion levels may also inhibit osseointegration of cementless components and lead to weaker fixation, with an increased potential for loosening. It is important to note that increased frictional torque in large-diameter metal bearings, in conjunction with head-rim contact, which produces an offset loading torque on the acetabular component, may also contribute to loosening, particularly of the acetabular component. Loose components can also produce metallic wear products. There has been one reported series of metallic wear due to fretting corrosion of cemented stems with MoM bearings. These factors need to be considered in patients with elevated metal ion levels in addition to the state of wear of the bearing surfaces.

**Other bioengineering considerations and causes of failure**

Other biomechanical factors that contribute to the failure of MoM bearings include acetabular component loosening and femoral neck fracture in surface replacements. The latter has been associated with notching of the femoral neck, malposition of the head and impingement of the femoral neck on the acetabular component. The reduction in acetabular component profile may lead to an increased incidence of head-rim contact and wear. Loosening of the acetabular component may result from higher frictional torque in MoM bearings, and may also be associated with head contact on the rim, which can produce a high frictional torque on the fixation interface.

**Do other bearings tolerate adverse conditions and head-acetabular component rim contact?**

There is no doubt that head-rim contact occurs with all types of bearing. In ceramic-on-ceramic bearings, translational malposition was found to produce head stripe wear whereas rotational malposition up to 60° did not. However, only a small increase in wear was found inalu-
mineral ceramic-on-ceramic bearings (up to 1 mm³ per million cycles) under adverse conditions, which was less for the tougher alumina ceramic matrix composite Biolox Delta. In polyethylene bearings, rim contact did not increase surface wear and in some situations reduced it, and damage to the head did not occur. However the elevated contact stresses associated with rim contact have produced polyethylene fatigue failure (often described as wear), particularly in the past with polyethylene that became oxidised. Fatigue failure due to head-rim contact remains a potential problem with highly cross-linked polyethylene and with polyethylene that may oxidise in vivo. However, apart from isolated cases, fatigue failure has not been a problem with cross-linked polyethylene acetabular components.

Conclusion
Under ideal conditions with concentric well-positioned components, the wear in MoM hips is low but when adverse conditions outlined above prevail the wear rate can increase by ten to 100 times and produce clinical ion levels well above 5 ppb. It is both the incidence of head-rim contact and the increased rate of wear in MoM bearings that lead to an increased rate of failure.

Good long-term clinical outcomes have been achieved in some series with full hemispherical MoM bearings. In other series, mainly surface replacements, higher than expected rates of failure have been experienced; some of these can be attributed to high wear rates and ion levels associated with contact between the rim of the acetabular component and the femoral head.

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References