# Tribology and Biotribology

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Reader in Biotribology
Newcastle University
25th October 2010

## Overview of lecture


- Tribology and biotribology
- Fundamentals of friction, wear and lubrication
- Focus on total hip replacement (THR)
- Metal-on-Polyethylene THR
- Metal-on-Metal THR
- Ceramic-on-Ceramic THR
- Compliant layer THR
- Research at Newcastle

## Tribology fundamentals

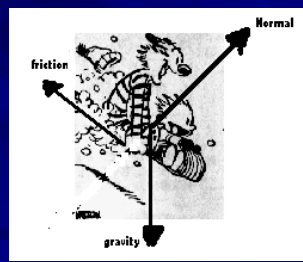
Jin et al, *Biotribology*, Current Orthopaedics, 2006, 20, 1, 32-40

Joyce, *Biopolymer Tribology*, in *Polymer Tribology*, Imperial College Press, 2009, 227-266

## Definition of tribology

- Tribology, from the Greek *tribos* 'to rub'
- The science of interacting surfaces in relative motion, including friction, lubrication and wear
- Biotribology is this science related to the body
- Primarily synovial joints and replacement joints

## Friction




## Friction (1)

- Friction force is a resistance to motion
- With no lubricant:
  - Friction force is proportional to normal force $F = \mu N$
  - Friction is independent of velocity
  - Friction is independent of apparent contact area
  - Friction is dependent on real contact area (1 to 0.0001% of apparent contact area)

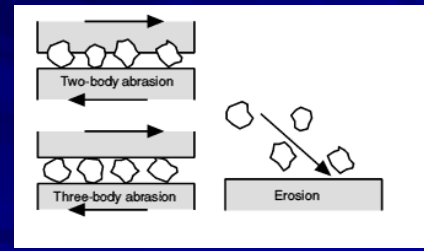
## Friction (2)

- Friction force (F) = $F_{adhesion} + F_{ploughing}$

Due to chemical bonding at the asperity contacts

Due to breaking and deforming of one asperity by another

## Wear




## Wear (1)

- Wear is the progressive loss of material from a surface. Various wear regimes:
  - Adhesive – due to bonding
  - Abrasive – due to hard asperities
  - Fatigue – due to cyclic stresses
  - Erosive – due to relative motion with a fluid containing hard particles
  - Corrosive – due to chemical reactions

*May occur singly or in combination*

## Wear (2)

- Wear can be measured as a depth, but volume is much better
- Generally wear volumes:
  - Increase with load
  - Increase with sliding distance
  - Increase with surface roughness
  - Decrease with surface hardness
- However, many other factors can be involved in the wear process

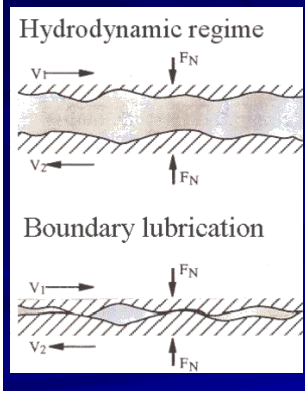
## (Archard) Wear Equation

- Volume loss ($mm^3$) = Wear factor k ($mm^3/Nm$) x Load (N) x Sliding distance (m)
- Volume loss is proportional to load and sliding distance
- Arc length = Radius x θ
- So if we compare an implanted 22mm diameter Charnley THR with a 54mm diameter Birmingham Hip Resurfacing, what might we expect?

## Lubrication

Adds a fluid film to separate surfaces

## Lubrication regimes




- Indicated by lambda ratio, λ
- Hydrodynamic lubrication (λ > 3)
- Mixed lubrication (1 < λ < 3)
- Boundary lubrication (λ < 1)
- Hydrodynamic lubrication (λ > 3) is to be preferred

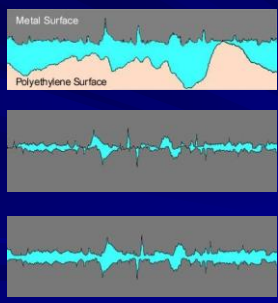
## Calculation of lubrication regimes

$$\lambda = \frac{h_{\min}}{\left[(R_{a1})^2 + (R_{a2})^2\right]^{1/2}}$$

$$\frac{h_{\min}}{R_x} = 2.80\left(\frac{\eta u}{E^* R_x}\right)^{0.65}\left(\frac{w}{E^* R_x^2}\right)^{-0.21}$$

- If roughness ($R_a$) increases, lambda decreases – lubrication gets worse
- $R_{a1}$ and $R_{a2}$ are the surface roughness values of each component, $h_{min}$ is the minimum effective film thickness, $R_x$ is the equivalent radius (m), η is the viscosity of the lubricant (Pa s), u is the entraining velocity (m/s), E* is the equivalent elastic modulus (Pa), and w is the load (N)

## Surface roughness and lubrication




- Typical metal-on-polymer joint, polymer relatively rough
- Metal-on-metal joint under typical mixed lubrication
- Resurfacing metal-on-metal joint. Fluid film lubrication possible

## Different types of hip prostheses


- 22mm diameter stainless steel head: polished to better than 0.050μm Ra
- Initially a low friction PTFE cup which wore quickly
- UHMWPE acetabular cup: roughness of 1.29μm Ra, radial clearance 0.2mm

## Lancet 2007

The operation of the century: total hip replacement

Ian D Learmonth, Claire Young, Cecil Rorabeck

Lancet 2007; 370: 1508–19

Published Online March 29, 2007

DOI:10.1016/S0140-6736(07)60457-7

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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.

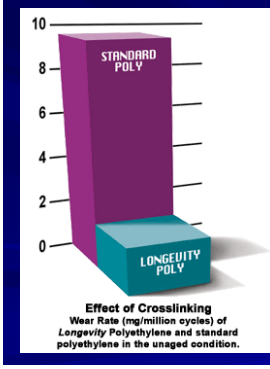
- Total hip replacement 'Greatest success in orthopaedics of the 20th Century'
- Cost-effective procedure, returning patients to pain-free independence

## THR failure due to osteolysis

- UHMWPE wear particles
- Volume: > 550mm$^3$ joint comes loose
- Size: majority in a range of 0.1-0.5µm
- Numbers: half a million particles at each step
- Provoke negative cascade of responses
- Loose prosthesis, radiolucent zones on X-ray, pain for the patient

***Therefore minimise the wear***

## Improved polyethylenes



**Effect of Crosslinking**
Wear Rate (mg/million cycles) of *Longevity* Polyethylene and standard polyethylene in the unaged condition.

- Cross-linked polyethylene (XLPE)
- Clinical and in vitro trials suggest 50-80% reduction in wear
- 'Familiarity' for orthopaedic surgeons
- Polyethylenes are more 'forgiving' to malposition

## Metal-on-Metal (MoM) THR

- 100 fold reduction in wear claimed compared with Metal-on-Poly
- Volumetric wear was reduced
- But particle size was smaller, typically 1nm rather than 1µm for UHMWPE
- Actual numbers of CoCrMo particles higher than UHMWPE
- Potential danger from metal particles?
- In US, 35% of THR were MoM (Bozic, 2009, JBJS)

## MoM resurfacing THR

- 46% patients under 55 years of age have a resurfacing implant (Steffen, JBJS, 2008)
- But since then the number of resurfacing operations has declined
- 'Pseudotumours' (Pandit et al JBJS 2008)
- Different resurfacing designs give different results

## Ceramic-on-ceramic THR

- Femoral head and acetabular cup made of hard ceramic material
- Potential benefits – low wear
- Brittleness was a concern
- Fracture rates now less than 0.1%
- Squeaking?
- Expensive

## Summary of key biotribological factors in THR

- Wear of PE leads to osteolysis and revision operations
- So reduce the wear
- Increase hardness: metal-on-metal, ceramic-on-ceramic
- Reduce surface roughness and maintain it
- Move from boundary to fluid film lubrication – increase head diameter, reduce surface roughness and radial clearance between head and cup

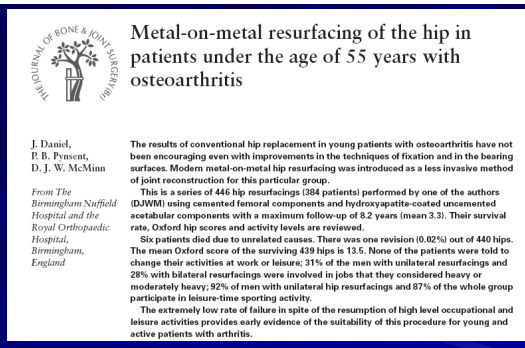
# Compliant layer THR

- Based on a concept of mimicking the superb natural joint with its compliant articular cartilage
- Polyurethane as the 'cartilage'
- Low friction and wear during motion
- But at 'start up'?
- Now in human trials


# Research at Newcastle

## Metal-on-Metal (MoM) Hip Resurfacing

## DePuy ASR™



Metal-on-metal resurfacing of the hip in patients under the age of 55 years with osteoarthritis

J. Daniel, P. B. Pynsent, D. J. W. McMinn

*From The Birmingham Nuffield Hospital and the Royal Orthopaedic Hospital, Birmingham, England*

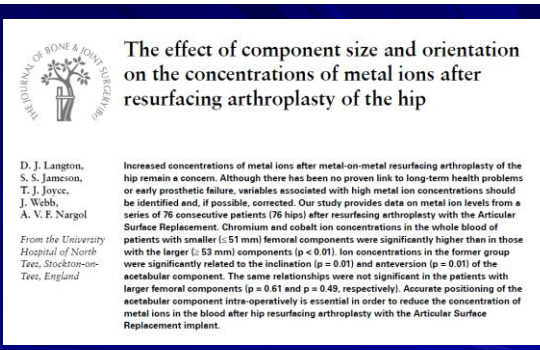
The results of conventional hip replacement in young patients with osteoarthritis have not been encouraging even with improvements in the techniques of fixation and in the bearing surfaces. Modern metal-on-metal hip resurfacing was introduced as a less invasive method of joint reconstruction for this particular group.

This is a series of 446 hip resurfacings (384 patients) performed by one of the authors (DJWM) using cemented femoral components and hydroxyapatite-coated uncemented acetabular components with a maximum follow-up of 8.2 years (mean 3.3). Their survival rate, Oxford hip scores and activity levels are reviewed.

Six patients died due to unrelated causes. There was one revision (0.02%) out of 440 hips. The mean Oxford score of the surviving 439 hips is 13.5. None of the patients were told to change their activities at work or leisure; 31% of the men with unilateral resurfacings and 28% with bilateral resurfacings were involved in jobs that they considered heavy or moderately heavy; 92% of men with unilateral hip resurfacings and 87% of the whole group participate in leisure-time sporting activity.

The extremely low rate of failure in spite of the resumption of high level occupational and leisure activities provides early evidence of the suitability of this procedure for young and active patients with arthritis.

- Daniel et al, 2004, JBJS (UK) 177-84
- One revision (0.02%) out of 440 hips
- Suitable 'for young and active patients with arthritis'



The effect of component size and orientation on the concentrations of metal ions after resurfacing arthroplasty of the hip

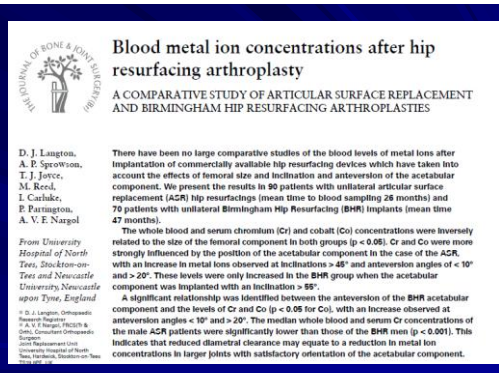
D. J. Langton, S. S. Jameson, T. J. Joyce, J. Webb, A. V. F. Nargol

*From the University Hospital of North Tees, Stockton-on-Tees, England*

Increased concentrations of metal ions after metal-on-metal resurfacing arthroplasty of the hip remain a concern. Although there has been no proven link to long-term health problems or early prosthetic failure, variables associated with high metal ion concentrations should be identified and, if possible, corrected. Our study provides data on metal ion levels from a series of 76 consecutive patients (76 hips) after resurfacing arthroplasty with the Articular Surface Replacement. Chromium and cobalt ion concentrations in the whole blood of patients with smaller (≤ 51 mm) femoral components were significantly higher than in those with the larger (≥ 53 mm) components ($p < 0.01$). Ion concentrations in the former group were significantly related to the inclination ($p = 0.01$) and anteversion ($p = 0.01$) of the acetabular component. The same relationships were not significant in the patients with larger femoral components ($p = 0.61$ and $p = 0.49$, respectively). Accurate positioning of the acetabular component intra-operatively is essential in order to reduce the concentration of metal ions in the blood after hip resurfacing arthroplasty with the Articular Surface Replacement implant.

JBJS (UK) Sept 2008, 1143-1151

For DePuy ASR™ ion concentrations linked to acetabular cup size and position



Blood metal ion concentrations after hip resurfacing arthroplasty

A COMPARATIVE STUDY OF ARTICULAR SURFACE REPLACEMENT AND BIRMINGHAM HIP RESURFACING ARTHROPLASTIES

D. J. Langton, A. P. Sprowson, T. J. Joyce, M. Reed, I. Carluke, P. Partington, A. V. F. Nargol

*From University Hospital of North Tees, Stockton-on-Tees and Newcastle University, Newcastle upon Tyne, England*

There have been no large comparative studies of the blood levels of metal ions after implantation of commercially available hip resurfacing devices which have taken into account the effects of femoral size and inclination and anteversion of the acetabular component. We present the results in 90 patients with unilateral articular surface replacement (ASR) hip resurfacings (mean time to blood sampling 26 months) and 70 patients with unilateral Birmingham Hip Resurfacing (BHR) implants (mean time 47 months).

The whole blood and serum chromium (Cr) and cobalt (Co) concentrations were inversely related to the size of the femoral component in both groups ($p < 0.05$). Cr and Co were more strongly influenced by the position of the acetabular component in the case of the ASR, with an increase in metal ions observed at inclinations > 45° and anteversion angles of < 10° and > 20°. These levels were only increased in the BHR group when the acetabular component was implanted with an inclination > 55°.

A significant relationship was identified between the anteversion of the BHR acetabular component and the levels of Cr and Co ($p < 0.05$ for Co), with an increase observed at anteversion angles < 10° and > 20°. The median whole blood and serum Cr concentrations of the male ASR patients were significantly lower than those of the BHR men ($p < 0.001$). This indicates that reduced diametral clearance may equate to a reduction in metal ion concentrations in larger joints with satisfactory orientation of the acetabular component.

JBJS (UK) Oct 2009

Contact Patch to Rim (CPR) distance – ASR™ cups more sensitive to position than BHR. An explanation for differences in clinical results

Early failure of metal-on-metal bearings in hip resurfacing and large-diameter total hip replacement

A CONSEQUENCE OF EXCESS WEAR

JBJS (UK) Jan 2010

D. J. Langton, S. S. Jameson, T. J. Joyce, N. J. Hallab, S. Natu, A. V. F. Nargol

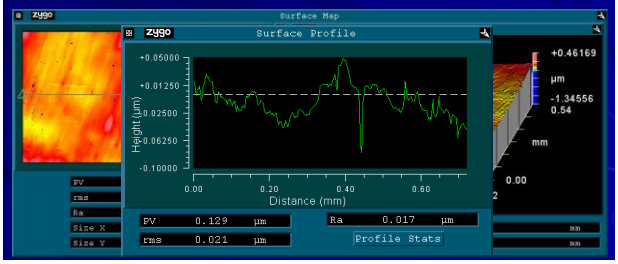
*From North Tees and Hartlepool NHS Trust, Stockton-on-Tees and Centre for Rehabilitation, Newcastle University, Newcastle upon*

Early failure associated with adverse reactions to metal debris is an emerging problem after hip resurfacing but the exact mechanism is unclear. We analysed our entire series of 660 metal-on-metal resurfacings (Articular Surface Replacement (ASR) and Birmingham Hip Resurfacing (BHR)) and large-bearing ASR total hip replacements, to establish associations with metal debris-related failures. Clinical and radiological outcomes, metal ion levels, explant studies and lymphocyte transformation tests were performed. A total of 17 patients (3.4%) were identified (all ASR bearings) with adverse reactions to metal debris, for which revision was required. This group had significantly smaller components, significantly higher acetabular component anteversion, and significantly higher whole concentrations of blood and joint chromium and cobalt ions than asymptomatic patients did (all $p < 0.001$). Post-revision lymphocyte transformation tests on this group showed no reactivity to chromium or cobalt ions. Explants from these revisions had greater surface wear than retrievals for uncomplicated fractures. The absence of adverse reactions to metal debris in patients with well-positioned implants usually implies high component wear.

Adverse Reaction to Metal Debris (ARMD) – an umbrella term to describe joint failures associated with pain, a large sterile effusion of the hip and/or macroscopic necrosis/metallosis

## Measurement of surface roughness

- ZYGO NewView non-contacting profilometer
- Typical changes 15nm to 100nm Ra
- Results in change from fluid film to boundary lubrication. Wear occurs over large sliding distance




SPECIAL ISSUE PAPER 317

**Tribological analysis of failed resurfacing hip prostheses and comparison with clinical data**

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DOI: 10.1243/13506501JET484

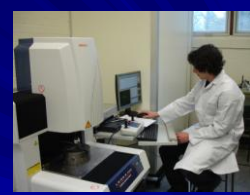
**Abstract:** Metal-on-metal resurfacing hip prostheses offer potential benefits over total hip replacement for younger and more active patients. Although some reported clinical results of resurfacing hip prostheses are excellent, other outcomes are less positive. To aid with understanding the balance of benefits related to these devices, analysis of failed resurfacing prostheses can contribute critical insights. However, because these implants are so new there are relatively few such prostheses available for independent *ex vivo* analysis. From a single-surgeon clinical cohort, a number of failed resurfacing hip prostheses were obtained and studied. It was found that roughness values of the articulating surfaces had increased so that the theoretical lubrication regime would shift from the fluid film to the boundary. In turn, this would likely result in increased wear from the articulating surfaces. High ion levels were seen in the patients from whom the explants were obtained, thus supporting the hypothesis that wear was linked with failure of the explanted hip resurfacing prostheses.

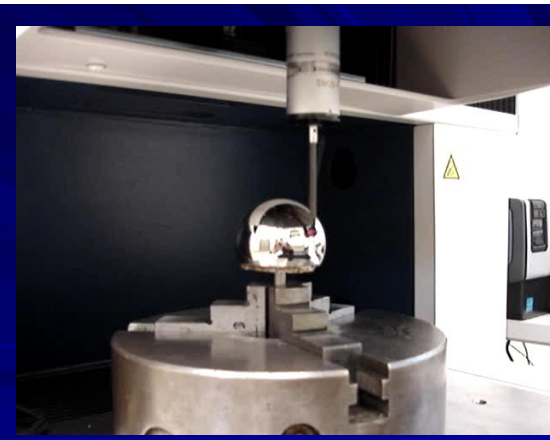
**Keywords:** metal-on-metal, cobalt chrome, hip resurfacing, hip prostheses, explant

J Engineering Tribology, 2009, 317-323

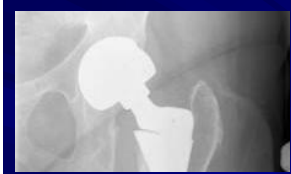
## Measurement of wear

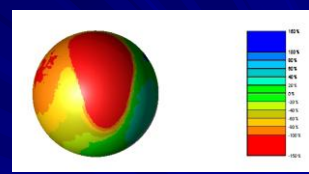
- Wear is a volume
- Co-ordinate Measuring Machine (CMM) recommended by international standards for measurement of wear in hip prostheses (ISO14242-2)
- State-of-the-art LEGEX 322 has an accuracy of 0.8µm





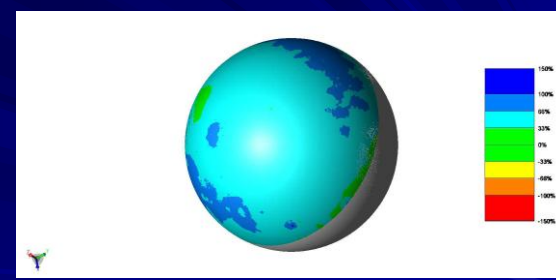
## ARMD ASR™ femoral head





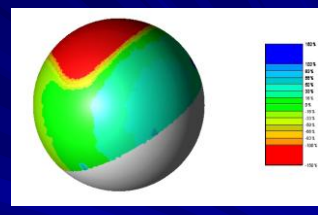
- Female patient, ASR™, failure at 35 months
- 45.5mm diameter, inclination 60°, anteversion 31°: Co 32.2µg/L, Cr 22.0µg/L
- Red area shows at least 20µm of wear depth, wear volume from head 20.2mm$^3$

## ASR™ femoral head – AVN failure



Cup inclination 38°, anteversion 17°, AVN failure at 3 years, total wear from head 1.3mm$^3$

## ARMD ASR™ head late fracture



- 64 yr old male, femoral fracture at 4 years
- 50.5mm dia, inclination 59°, anteversion 31°
- Red area shows at least 20µm of wear, wear volume from head 134mm$^3$

## Research at Newcastle

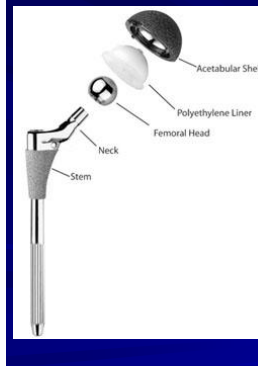

- Sept 11 2010
- DePuy ASR™ THR withdrawn worldwide 26 Aug 2010
- 93,000 implanted
- 1 in 8 failed and been replaced at 5 years
- Tissue destruction
- Due to excessive wear
- Huge worldwide impact on artificial hip joints


Johnson & Johnson faces £350m bill over 10,000 faulty hip operations

'I'm in constant pain, it has ruined my life'

Mail on Sunday 24 Oct 2010

## Overview of lecture




- Tribology and biotribology
- Fundamentals of friction, wear and lubrication
- Focus on total hip replacement (THR)
- Metal-on-Polyethylene THR
- Metal-on-Metal THR
- Ceramic-on-Ceramic THR
- Compliant layer THR
- Research at Newcastle

## Thank you Any questions?