Executive summary:

Summary

The EU funded project "Enhanced Durability Resurfacing Endoprosthesis" (ENDURE) ran from October 2009 to January 2012. The goal of ENDURE was to develop a high durability ceramic on polymer resurfacing hip prosthesis with a working lifetime in excess of thirty years. The project team achieved this by applying their unique expertise in state of the art design, manufacturing and evaluation techniques, to leading-edge materials technology in the form of carbon fibre reinforced poly-ether-ether-ketone (CFR-PEEK) and alumina matrix composite (AMC) bio ceramics. As part of this effort, new cost effective processing methods needed to be developed for the polymeric material. Verification of the new implant designs was conducted via computational and mechanical testing, ultimately leading to an extensive cadaveric workshop where the implant system and instrumentation were demonstrated in a fully representative environment by a surgeons specialising in hip resurfacing.

A unique attribute of the implant system is that unlike conventional counterpart resurfacing implants on the market today, it provides a metal-free alternative and possesses bone-like elasticity; these attributes help eliminate certain risks associated with traditional resurfacing materials: Cobalt-chromium implants currently in use are very rigid, and the load transfer to the bone is non-optimal, potentially leading to adverse bone adaptation or 'stress shielding', and weakened bone. In addition, they can cause excessive metal ion release and the associated complications that have recently gained a great deal of adverse publicity. The CFR-PEEK cup is made from a high-strength, wear resistant, biocompatible material; it enables more natural transmission of force through the PEEK hip socket to the pelvic bone encouraging more natural bone growth. The femoral head employs an extremely wear resistant, metal free AMC with high fracture toughness. In addition to this, a hydroxylapatite coating was employed on the backing surface of the cup to support bone tissue integration with the surface of the implant. The ENDURE implants follow the bone-preserving principle of hip resurfacing: they consist of thin-walled shells which replace the bearing surfaces of the joint articulation alone, instead of employing large metal stems and thicker cups, which require a substantial volume of bone to be removed. The project team has also redesigned the way the prosthesis is mechanically attached to the bone, avoiding the use of cement, and using a press-fit and an integral scaffold-type structure on the surfaces of the implant that contact the bone. The hemispherical ball and socket are tapped onto the prepared femoral head and into the acetabulum and anchored in place using these surface features for immediate primary stability.

Computational and pre-clinical experimental verification of the implant concept was central to the project.

Computational finite element (FE) models ascertained the stresses generated within each component both during normal gait movement and under extreme stumbling loads. The analysis indicated that the ENDURE system had good safety margin against failure. The models also looked at the cup-bone interface conditions and concluded that on the basis of mechanical factors alone, the whole cementless cup-bone interface surface could be capable of achieving fixation through bone in-growth.

An extensive experimental test programme was conducted to ensure the resurfacing system could withstand extremes of in service loading. Mechanical tests were devised with assigned load cases and pass criteria to represent the extremes of in-vivo loading. In particular, the test sequence included the simulation of malpositioning during implantation.

The consortium were able to confirm the good wear resistance in initial tests of the ENDURE hip system using a 10 station wear simulator and a programmable robot that simulated various series of movements such as walking or climbing and descending stairs on prototype implants.

A team of physicians at the University of Newcastle have demonstrated in operations performed on cadavers, that the ENDURE hip system can be set in place and, if necessary, removed without any difficulties. Preclinical studies have been completed, and end stage development work is being planned to allow the commencement of clinical studies. Partners in the EU-funded project are Aurora Medical, Medicoat, Hunt Developments, Ala Ortho, CeramTec, Invibio, The Fraunhofer institute, Biomatech and the Universities of Gothenburg and Southampton.

Project Context and Objectives:

Summary Description of Project Context and Project Objectives

The treatment of younger patients with severe hip disease using a conventional Total Hip Arthroplasty (THR) presents a challenge. The success rate of the THR is currently very low within the first 16 years of implantation. To overcome this Finsbury instruments, in conjunction with surgeons, Midland Medical Technologies Ltd (MMT) and Doncaster's Centaur Precision Castings, developed the Metal on Metal (MoM) Birmingham Hip Resurfacing (BHR) system, which was developed for MMT. However, the MMT was subsequently bought by Smith and Nephew (USA company) during 2005. Evidence suggests that the MoM resurfacing provides an ideal solution for implantation into younger patients who have a more active lifestyle with the survival rate being 93% after 3 to 5 years over a conventional THR. However, there is concern about metal wear debris and its systematic distribution throughout the body. Several studies have reported high concentrations of cobalt and chromium in the serum and/or urine of patients with MoM resurfacing implants. Potential toxicological effects of the elevated metal ions have increased concerns about safety of MoM implants. This is a particular concern in younger and active patients in whom life expectancy after implantation is longer. Because patients who receive a MoM hip arthroplasty are shown to be exposed to high concentrations of metallic ions, the Medical Advisory Secretariat performed literature searches for the adverse biological effects of cobalt and chromium. Cobalt and chromium make up the majority of the substrate material used in the manufacture of MoM implants.

Concerns have been raised recently due to high levels of cobalt and chromium measured in blood and serum samples of patients with MoM devices. These concerns relate to the possible systemic effect of metal ions released by MoM prosthesis in terms of genomics, as well as immulogy , and histology, and reviews have recently been published , into the ion levels and their biological effects were marked when wear was abnormally increased, with low carbon (less than 0.2%) implants and loose or poorly positioned implants.

In November 2006, a meeting was organised by Dr Case, University of Bristol, UK, with a panel of world experts in various medical fields where metal ions were thought to have a potentially detrimental effect. It was concluded that a risk to benefit analysis should performed for individual patients wishing to have a MoM implant. The long-term exposure concerns were related more specifically to younger, more active patients wishing to have children and to maintain their active life style. It was concluded that a risk benefit analysis of the patient situation should be implemented. For those patients wishing to have children post joint replacement, it was decided that further follow up studies were required, with a particular focus on the potential passage of the genetic damage to offspring in younger patients.

MoM resurfacing technology is superior to that of conventional THR implant for younger patients; however, the MoM has a series of potentially long-term problems of its own. To overcome these problems the partners in the ENDURE project developed a ceramic on polymer resurfacing hip prosthesis. Like that of the MoM prosthesis the ceramic on polymer resurfacing prosthesis will only cover the femoral head thus retaining all of the desirable properties associated with retaining an intact femur.

Using the following key innovations developed during the course of the ENDURE project the partners we able to produce a new resurfacing hip prosthesis that gave significant advances over current existing systems.

These Key innovations include:

-Fabrication of a resurfacing (BHR-type) femoral, hemispherical ball-head and cup from ceramic and polymeric materials.

-The use of new materials, and processing methods to achieve a non metallic low ware resurfacing hip system.

-Development of a flexurally tough alumina matrix composite (AMC) ceramic femoral head and thin walled reinforced polymer acetabulum cup.

-An innovative coating process that will allow for full bone integration with the implant.

-A novel design that includes the bone as part of the construction.

-An advanced low impact surgical procedure to reduce trauma during the operation.

The ENDURE system resurfaces the femoral head similar to that of the MoM system but unlike this system the ceramic wear particle will remain inert within the body thus eliminating any concerns relating to the long term effects of ions. It is well known that the use of ceramic and polymeric materials will lower the coefficient of friction between the mating surfaces and as a result will reduce the amount of wear and thus debris generated during the normal operation of the joint.

OVERALL PROJECT OBJECTIVES

Our main objective was to develop a high durability ceramic on polymer resurfacing hip prosthesis that has a long working lifetime ideally in excess of thirty years. This was be achieved by unique combination of the best, established technologies, plus the additional advantages of novel AMC bioceramics, new processing methods and polymeric compounds. In order to realises these objectives we broke them down into the following categories.

Scientific Objectives

Our scientific objectives were those relating to issues of durability, via influences in physical wear phenomena and biocompatibility.

We set out to:

-Enhance the understanding of wear processes in AMC ceramic / polymeric compounds that guided the design and material choice for elimination of significant wear in joint prostheses.

-Identify the factors that influence wear by analysing of the friction/load relationship.

-Enhance the understanding of factors influencing the effectiveness of lubrication films in prosthetic joints in near in-vivo conditions.

-Create a working synthesis of novel material and innovative design features that will enabled the consortium to:

• Perform Finite Element Analysis (FEA) to determine the optimal implant geometric design for implant-bone fixation and maintenance of healthy bone structure.

•Combine FE analysis and experimental work to derive the best bearing design in terms of minimal wear and friction by promoting hydrodynamic lubrication.

•Determine Coating strength on the implant

•Using the FEA model of the geometrically correct profile to determine the wear patterns and rates for the individual materials.

•Predict the hydrostatic film boundary with respect to the predefined geometrically correct profile.

•To determine the biocompatibility of the materials.

This enhanced knowledge was attained using the protocol described in the work package plan and determined was used to design the physical component parts, the configuration of the material sub-components in the acetabulum cup, and the configuration of the

hemispherical femoral ball. In particular this included the specification for the degree of asphericity of each major component, and the gap size for lubrication.

Technological Objectives for the device: The technological objective was to acquire the science to enable the development of the first durable, long-life hip resurfacing joint prosthesis that would:

-produce a low friction/wear coupling by accurate and precise grinding of the component faces to the specification and tolerance identified during the work packages.

-achieve volumetric wear rates ≤ 0.8 mm3 per million cycles under simulated steady state in-vivo lubrication conditions, by accurate and precise machining to asphericity specifications and tolerance identified.

-Reduce the size of the wear particles so that they do not exceed 0.1µm, by application of design specification from work package 1.

-Avoid adverse sensitivity and have complete biocompatibility by choice of AMC as the bioceramic and polymeric / CF PEEK materials used for the construction.

-Ensure complete and stable osseointegration within the first 3 months following surgery by a coating combination of Titanium and hydroxyapatite, applied through the development of the vacuum plasma spray technique.

-Improvement of operative technique and instrumentation to improve optimise alignment and reduce the risk of femoral neck notching to achieve optimal range of motion and avoid post-operative femoral neck fractures.

-Increase of candidate patients including women of child bearing age.

Economic Objectives

As well as the technical objectives the consortium partners also addresses the economic need for the technology developed during the course of the project. The results of the economic study showed that by the end of year 5 after the project, and through a network of trans-national and cross-sectoral licensees, the consortium would be able to sell the new joint technology over the time period:

-Gain significant market share to compete with the USA and other major implant manufacturers displacing at least 2.5% of the estimated 3 Euros Bn p.a Global hip implants allowing the group of small and medium-sized entreprises (SME)'s to gain a footing into the Global market place by the development of the new prosthesis.

-Obtain for the small and medium-sized entreprises (SME) partnership an additional 5% of the 800,000 implant sales worth an estimated 395 million Euros per annum after ten years post project including the anticipated compound growth rate of 15% per annum. We estimate that based on the average cost for the manufacture of hip resurfacing implants of 1,800 Euros with an average profit of 325 Euros we will increase the profit of the SMEs involved by 60 million Euros per annum.

-The increase in turnover will have the effect of increasing employment within SMEs companies based on 1 person per 140,000 Euros by (395m / 140,000 = 2800) an estimated 2800 jobs after the 10 year period.

-The technology will reduce the number of patients needing revisional surgery from the current 168,000 by 64,000 each year after ten years. This will have the effect of reducing the cost of revisional implant surgery by 40% and save the European health authorities an estimated 902 million Euros per annum. The cost savings will allow the health care units to reallocate this funding to other areas of the health care sector, allowing these to benefit from the additional funding.

Enabling Innovation Related Objectives

To achieve the societal and economical objectives that come from the dissemination and exploitation of the research results the consortium partners have defined an enabling set of objectives.

To enable innovation through the project team and to benefit Europe the objectives are:

-Collation and preparation of the results of the project into a suitable format and apply for patent protection of the results of the project covering the manufacture of the novel AMC ceramic/polymeric hip technology.

-The transfer knowledge from the RTD performers to the SME participants has been achieved using technology transfer events and interactions.

-To disseminate the results and benefits of the knowledge and technology developed beyond the consortium to potential users such as healthcare/surgical, dental, veterinary, scientific and specifically:

--100 SME companies from the implant, trauma, dental, general surgical and scientific sectors will be contacted to promote the project results.

--Three trade or sector specific shows will be attended these will include Medica, MDT and MedTec.

--10 SMEs from the non-competitive industrial medical sector stimulated to apply or use the science and technology results in their future product strategy.

--Four SMEs engaged with, in detailed knowledge or technology transfer, by the end of 2015.

--10 licensees to adopt the results in the generation of new products or systems by the end of 2015.

Societal and Policy Objectives are to benefit society by:

-Reduce the number of surgical revisions following implantation of a medical device. Based on the fact that the consortium intends to take 5% of the European market share by 2018 we estimate that the ENDURE project will reduce the number of revisions by 40% for those fitted with the new resurfacing implants, saving 66,400 patients from the risks, immobility, and discomfort of revision surgery

-As a result of the reduction in the numbers of people requiring revision surgery, the ENDURE project will have the affect of allowing reallocation much-needed medical resource to other areas.

Project Results:

The Main Science and Technology (S&T) results / foreground.

Introduction:

In order to deliver the work within the ENDURE project each objective was broken down into a separate work package.

Work Package 1 - Design Foundation

The objective of work package 1 was to define the design envelopes for the Femoral and Acetabular components

Literature Search for the Material data

During this task several aspects of the prosthesis component design were considered and our research showed that currently the most common bearing components used is metal on polyethylene. The polyethylene is housed in a metal backing and implanted on the acetabular side. Other common bearing types are metal on metal and ceramic on ceramic. Although some are more successful than others, all of them still experience problems. The common problems associated with each implant range from high wear rates, stress shielding, osteolysis to implant loosening. In order to improve the longevity of the prosthesis, these problems must be overcome. This could potentially be achieved by the use of a new material implant combination.

Ceramic materials have been used successfully for the manufacture of hip joint replacement. These are used as a bearing material, articulating against itself or against polyethylene. These devices includes a metal outer shell in order to allow for an in growth surface to be added to the outer surface of the component, which would not be achievable on ceramic or polyethylene materials alone. The in growth surface is critical to the short and long term fixation between the implant and the surrounding bone. However, problems with fixation on the acetabular side are often reported, and loose cups are a common reason for revision in hip replacement. These problems are attributed to the high stiffness of the acetabular replacement component, due to the presence of a stiff metal shell. Polymer materials offer a solution to the stiffness mismatch. Various polymer materials have been successfully used in other areas of orthopaedics (spinal) and in dental applications. This has led to a growth of interest in polymers for use on the acetabular side of hip replacements. A polyaryletherketone (PEEK) biomaterial launched by Victrex in 1998 and marketed for medical use has many advantages over metals including elimination of imaging artefacts and the ability to view tissue/bone growth and repair using x-rays. The addition of a filler

material in the PEEK namely carbon fibre formulates a different grade called CF-PEEK. The materials properties can be adjusted by varying the percentage of carbon fibre inclusion; this is of particular interest to the design of a replacement construct where some compliance is required at the bone interface whilst bulk strength is a basic requirement for the component itself. The properties of both filled and unfilled PEEK materials must be fully understood and verified for their use in-vivo and to determine where CF-PEEK is more appropriate to use over unfilled PEEK.

The Required Range of Motion (ROM)of THR Implants

In normal THA prosthesis, the range of motion is maximised through the use of a large head diameter and a small neck diameter on the femoral stem component which enhances the hip performance by allowing greater range of motion before the components impinge. (Chandler et al. 1982, Barrack 2003, Bengs et al. 2008) Hip resurfacing decreases the head to neck ratio as the natural femoral neck is retained. Impingement can occur when the retained femoral neck abuts against the acetabular component or anterior acetabular bony wall. This can be painful and restrict motion. The ISO standard 21535 states that 100° flexion/extension; 60° abduction/adduction and 90° internal/external rotation is required. However, even the earliest literature states that a greater range of motion needs to be achieved in order to allow everyday tasks to be performed. Johnson and Smidt (1969) and Roach and Miles (1991) have shown flexion/extension values in the range of 125-135° which is higher than the value recommended in the standard. Clearly if THA implants are designed to this specification, the patient's post operative ROM will be limited.

Kluess et al. (2008) performed a study on how the implant designs affect the flexion/extension and internal and external rotation angles that are achieved post-operatively. The results of the study highlight that the current implant designs do not achieve the required ROM in all patients. Using the data gather from the literature searches it was possible to generate a simple FE model that considered various potential loading scenario, simulating activities more demanding than the conventionally modelled walking gait, and a more accurate prediction of worst cases stresses generated within the construct during service was obtained.

Design aspects specific to ceramic material use

Finite Element (FE) analysis studies have particular use in the pre-clinical analysis of new prosthesis designs and are used to make safe design decisions with regards to performance. FE models also provide technical evidence during the regulatory submission process, a necessary step in most new product development projects. Whilst it is relatively easy to simulate ISO tests of implant components mounted in simple elastic supports, it can be argued that this does not represent the whole range of typical loading conditions experienced by an implant in-vivo. Even to begin to recreate these conditions, it is necessary

to mount the implant in realistic supporting bone with geometry with materials properties derived from Computer Tomography (CT) data. The FE model developed to assess the stresses the component may be subjected to during its life in vivo was developed using state of the art methods in order to improve its accuracy. In particular, surgical data (CT scanned bones) were used to generate the bone models. The establishment of design requirements, including pass criteria for the output of the FE analysis, is critical to the safety of the design.

FE Models of resurfacing femur

The following most fundamental design criteria were considered in this study:

-The volume of damaged bone under stumbling and falling loading conditions must be lower for the new designs than for the ADEPT or BHR prostheses, hereby referred to as 'the traditional design',

-the percentage volume of bone with sufficient remodelling stimulus to generate stress shielding and hypertrophy around the prosthesis will be lower than for the traditional design, and

-the peak stresses in the new design must be considerably below the fatigued fracture strength for the material. Absolute strength tests are beyond the scope of this report, but extreme stumbling loads must be sustainable safely.

Details for Ceramic Manufacturing Work Package

Ceramic heads were produced by the following process:

1.powder batch preparation, e.g. wet milling and spray-drying powder granulation,

2.pressing into a cylindrical billet, of low theoretical density and strength,

3.green machining, into an approximate, over-sized shape,

4.thermal 'presintering' to achieve approximately 96% theoretical density,

5.hot isostatic pressing (HIP) in oil or gas to achieve appr. 100% theoretical density and strength,

6.hard machining of the bearing surface, to precise, tightly toleranced dimensions,

7.polishing the bearing surface to the required surface roughness,

8.laser marking with part and serial numbers,

9.proof testing, and

10.final inspection.

The manufacturing process has been developed to produce heads of adequate strength to avoid fracture in-vivo, through careful control of grain size (in powder processing), volumetric flaw content (in pressing, sintering and HIP) and surface flaw content (in progressive machining and polishing). The diameter, roundness and sphericity of the final bearing surface are critical to a bearing component's wear performance, so the manufacturing process was also designed to allow target bearing dimensions to be achieved within tight tolerances.

The particular difficulty with the production of ceramic resurfacing heads is the lower wall thickness than modular heads. This is relevant to the bearing surface dimensions, as gripping the piece for machining in a chuck may distort it, so that it deviates from the required roundness when it springs back upon release. Although specific details of manufacturing processes, fixtures and target dimensions and tolerances cannot be released, this work package involved:

-the further development of pressing of larger sized billets for green machining of resurfacing heads and other CT products with large diameters based on existing and established technology

-the development of machine mounting fixtures to allow the thin-walled resurfacing component to be gripped and machined with sufficiently low distortion to give adequate final roundness and sphericity.

This permitted a series of resurfacing head shaped prototype prostheses to be produced, allowing mechanical testing to commence. The approach involved developing the existing manufacturing technique with as few changes as possible, as past clinical results of other manufacturers have demonstrated the risk associated with departures from known techniques.

Both the design and the manufacturing techniques were verified with mechanical testing.

Design aspects specific to CF-PEEK material use

There are many design features that are required in order to make a new resurfacing hip system successful. The areas that required extensive research were the geometry and

tolerances between surfaces as well as the overall design. It was important to also include the design principles of the dedicated surgical instruments.

From the Material Data report it was confirmed that the femoral head would be manufactured from BIOLOX ceramic, whilst the acetabular cup would be made of carbon fibre reinforced polyetheretherketone (CF-PEEK) or a combination of CF-PEEK and unfilled PEEK.

A literature review was performed on performance of the current acetabular cup designs that employ CF-PEEK as their bearing surface which include the Cambridge and MITCH cups. Fixation methods in the form of a coatings and porous layers to encourage bony in-growth and improve initial fixation of the cup were also explored.

The investigation also looked at patents on PEEK acetabular cups, coatings and porous outer surface.

Designs ideas discussed during the ENDURE kick off meeting were reviewed to determine the optimum option and each design was scored against the following criteria: complexity, manufacturability, bony in-growth, surface finish, novel idea, initial fixation, coating ability and difficulties to grade each design. The optimum design includes a multiple layered design consisting of CF-PEEK MOTIS as the bearing surface and a porous layer of PEEK OPTIMA.

Work Package 2 -.Implicit and explicit computational analysis

The aim of Work Package 2 was to produce computational analysis tools:

1) to inform the design of the developing implant concepts,

2) for their initial theoretical structural verification, and

3) to enable physical tests to be developed that would reproduce clinically representative stress distributions in the implant components, for their more concrete physical test verification.

The goals of the structural analysis were to predict:

-the bulk stresses in the bone supporting the implants,

-the stimulus and progression of bone remodelling around the implants and

-the fixation interface conditions, indicating their long-term stability,

-the bulk stresses in the implants under a range of in-vivo loading conditions (normal and traumatic scenarios), and

-the bulk stresses in the implants under surgical impact loading conditions.

First, a matrix of load cases was produced by conducting a review of the scientific literature and published biomechanical data of live patients with instrumented joint replacement implants, in order to capture a wide range of normal activity load cases and traumatic loading events. As a second modelling input, intact and generic implantable pelvis and femur Finite Element analysis models were generated using live patient CT scan data. These models were implanted with several iterations of the implant designs, allowing progressive informed design development.

Analyses were conducted to verify the ENDURE cup design. First, monoblock CFRPEEK, CoCr and Delta cups were implanted in the replica hemipelvis model, with ideal implant positioning, for three (smallest, largest and mid-range) sizes. The CFRPEEK cup was predicted to generate a reduced remodelling stimulus in the supporting bone than the stiffer metal and ceramic cups, indicating that it would preserve the density of the supporting bone for longer. The worst-case (smallest) size CFRPEEK cup was predicted to have a peak stress of 35.5MPa under walking loads, giving a safety factor of 2.7 compared to the material's quoted 95MPa fatigue strength. All cup materials were predicted to produce comparable levels of implant-bone micromotion, indicating that biological fixation through bone ingrowth would be achievable. Second, FE analysis of incorrect implantation was conducted to verify the cup's strength with excessive inclination causing edge loading. Even at worst-case steep inclination, the peak stress in the worst-case cup did not exceed 50MPa under walking loads. A third FE analysis modelling the same conditions but including incomplete cup rim support produced a peak stress of 66MPa, still a safety factor of 1.4 compared to the fatigue strength and 2.3 compared to the tensile strength. Finally, FE analyses of the cup deflection under implantation 'pinch' loading and in-vivo gait loading were conducted, which indicated the likely change in implant shape and therefore the required bearing design clearance to produce the required net clearance for correct bearing performance when implanted and in service.

Second, analyses were conducted to verify the ENDURE head design. The modelling results supported the fundamental design philosophy in terms of the stress in the prosthesis and the strain in the supporting bone. Specifically, it was predicted that incorporation of the stiff ceramic material would not lead to additional adverse bone adaptation in comparison to existing metal implants, thanks to the proposed geometric design developments over the

precedent technology. The model indicated that with incorporation of a shortened metaphyseal stem design in comparison to currently clinically used metal resurfacing head designs, the net increase in stress shielded bone volume could be minimised, although the analysis supported the use of conventional cemented implant fixation methods, over less forgiving cementless fixation. The analysis indicated peak ceramic tensile stresses between 143 and 305 MPa, which it should withstand safely, indicating a safety factor of 3.8 compared to the characteristic flexural strength of the material. The models also analysed the implant fixation surface conditions, and indicated a maximum tangential micromotion (sliding) displacement of 35.9 μm and maximum normal (opening) micromotion of 20.2 μm. The scientific literature suggests that bone in-growth can be achieved with small micromotions (in the range 20-56 μm), so this supports the generation of a stable implant-bone interface, in theory.

On the basis of the in-vivo predicted stress distribution, mechanical tests were designed with load cases and pass criteria to represent the extremes of in-vivo loading. Three tests were developed to reproduce the three main stress concentrations in the structure. First, a stem test evaluated the bending stress generated at the root of the stem. Second, a crush test evaluated the strength of the head's shell under worst-case implant malpositioning. Third, an ultimate strength test evaluated the burst strength of the whole head with correct positioning. Additionally, an interface torque test determined the strength of the prosthesis-bone interface under worst case loading conditions, where the torque axis aligns with the head axis. All three tests were designed with the FE modelling procedure, and the design was verified in theory when these tests were simulated. The subsequent Work Package 6 conducted these tests physically, for more concrete implant design verification.

Finally, explicit FE analyses were conducted of the proposed ceramic head's structural strength under dynamic impact loading, representing surgical impaction during implantation. The worst-case, highest load impacts were modelled, when the head is finally seated on the bone and its support is therefore stiffest. A variety of potential loading conditions were incorporated considering variability in the angle of applied force from the impactor. An off-axis impactor angle was found to modify the stress distribution in the implant adversely, by introducing bending stresses in its stem. However, the peak stresses were predicted to be 67.5MPa in the worst (smallest size implant) case, considerably below the strength of the material. Finally, physical impaction tests were conducted to assess the validity of this novel analysis methodology. The characteristic impact force-time profile predicted by the FE model was observed in the physical tests. The FE model was found to over-predict the peak stresses and under-predict the impact duration, probably due to necessary simplifications in the modelling of the test support structure. As such, the models represented a slightly worse than realistic case, so were validated for the verification process.

Work Package 3 - Primary fabrication development

All tasks in this WP were associated with the manufacture of the prosthesis components and the development of the tooling / manufacturing processes needed to produce the components. The work performed focused on the prototype manufacture of the femoral and acetabulum components addressing the hard machining of the ceramic head and the surface finish process to obtain the correct clearances and geometry. During this work package the potential manufacturing route for the acetabulum cup and the required fixation of the cup into the pelvis along with the surface geometry of the articulating surface was established.

Ceramic Manufacturing

In order to manufacture the femoral head a pre form tool of the head was manufacture, this perform tool allowed cylindrical billets to be made from which the green state femoral head where machined. The green state femoral head were generated as over-sized components that would reduce to their near final shape during the following operations.

The green state components were thermally pre-sintered to achieve an approximate 95% theoretical density. This was followed by a hot isostatic pressing process which gave the final components a 100% theoretical density and its final strength. The femoral components then went through a hard machining process which formed the outer and inner surfaces to the tight dimensions required. The outer surface was then polished to give the correct RA required and the inner surface was laser marked prior to proof testing and final inspection.

Prototype CF-PEEK manufacturing

Injection mould tooling for the manufacture of the CF-PEEK cups was designed and manufactured speificaly for the very exacting demands of the materials. The first set of tooling produces oversized cups with no surface feature on either the inner face or the back of the cup. The idea behind the manufacture of the oversized cups was that these could be machined to form the final cup geometry for testing purposes. At the same time as these were being manufactured rapid prototypes of the cup were also produced for assessment from the point of ease of manufacture and the benefits of the interlocking with the bone once implanted. Several tests were performed with the novel outer surface geometry to identify the optimum shape to gain the best fixation.

Following a review of all of the parameters required by the cup with respect to the materials properties, mechanical stability and range of movement a series of cup designs were assessed following the review a final design was derived this was the Horseshoe cup were the cup design mimicked the actual design of the acetabulum. The design incorporated the

acetabulum notch in the Lunate (articular) surface. The design allows the cup to flex with the adjacent bone giving a more physiological bone strain pattern, to reduce stress shielding, but not to the extent that there is excessive cup-bone interface micromotion, which would result in poor initial stability. The raised area also allowed for loading of the horseshoe segment of the acetabular socket mimicking what usually occurs on the articular cartilage. The thickness of the cup was reduced to conserve bone, and allow a larger bearing diameter to be used whilst minimising dislocation risk. At the bottom of the recess is a hole which is designed to simulate the actual acetabulum allowing for the collection of synovial fluid. It also acts as a location point for the impaction instrumentation.

Having defined the internal geometry of the cup the research focused on the external surface which had to integrate with the acetabulum. Several proposed ideas were generated for an interlocking mechanism with the acetabulum. These included the incorporation of a location pin augmented with fins which once pressed into the acetabulum trabecular bone would give an initial good fixation.

The single pin location was developed together with the alignment instrumentation needed to implant the cup in the correct position. The instrumentation for the alignment of the cup was based on the Peter Ring implant procedure where the location pin runs along the ilium.

Results

As a result of the testing the final design of the femoral head and acetabular cup was established. The femoral head was made from Biolox Delta ceramic using predefined manufacturing protocols, e.g. hot isostatic pressing followed by hard machining and polishing to achieve an Ra of 0.02µm. The femoral component consisted of the short location stem capable of withstanding a 1.27kN stem tip load and a shell that will with stand a tensile stress load of 5.6kN. The inner surface of the head was coated with a Ti and HA coating with thicknesses of 30µm and 70µm respectively.

The acetabulum cup was manufactured from CF-PEEK by advanced injection moulding techniques; once moulded the hole in the bottom of the horseshoe was drilled. As can be seen in Figure 5 the cup has been designed with the single pin location which has been offset to allow for the maximum range of movement. The inner surface has been designed to have a similar Ra value of 0.02µm to that of the femoral component. The back of the cup has been designed to integrate with the dense trabecular tissue within the reamed acetabulum the design carries a series of fins that will mesh with the bone tissue. The final design mimics the actual acetabulum and the material characteristics have been developed to minimise the stress shielding under normal gait conditions.

The outer surface of the cup has a dual coating consisting of a 30µm Ti layer over the whole surface with an increase in the coating around the circumference of 70µm for a width of 10mm to show the surgeon the position of the cup following implantation. This will then be over coated with a 70µm coating of HA to gain good secondary fixation with the surrounding tissue.

Work Package 4 - Development of secondary coating

Under work package 4 an investigation in to the potential coating methods for the integration of both the femoral and acetabulum components was performed. This investigation consisted of vacuum plasma coating trials on the selected materials i.e. a Ceramic substrate and samples of CF-PEEK. These samples were coating with hydroxyapatite HA, Titanium Ti and a combination of Ti and HA. Several trails were made using the different combinations of the coating at different thicknesses and with different substrate preparations such as shot blasting with silica media and with HA powder. The preparation with the HA was performed to reduce the potential of contamination from the alumina blasting media, however the cost of blasting with HA proved significantly more than the cost associated with cleaning off the alumina media residue. Following coating mechanical testing was performed on the samples to determine the mechanical bond strength of the coating.

Development of dual coating process parameter options

During this task a study of coating a Ti foam backing bonded to the back of the CF-PEEK acetabulum cup was analysed. Following this extensive research it was decided not to generate a foam material for the back of the acetabulum cup as this would prove too flexible for good early fixation of the cup. Therefore our investigations focused on the coating of the CF-PEEK directly with a HA coating and a Ti with HA coating. In order to ensure that a good adhesion was achieved a series of grit blasting tests was performed on the substrate material. Two medias were used for the grit blasting process, these were conventional Alumina and the other media was HA. It was decided to try the HA to prevent the risk of cross contamination from the Alumina media, the results of this test showed that both materials provided a suitable surface finish for the adhesion of the plasma sprayed coatings. However the cost of using the HA was considerable more than that of the Alumina media and from a cost exercise this will probably be the media used during production.

For the coating process it was necessary to reduce the heat transfer into the cup, in ordered to achieve this we had to increase the velocity of the robot arm while at the same time reduce the powder size as this reduced the amount of energy required to melt the powder. The plasma gas used for the trial was approximately 25,000°C and the velocity at which the medial left the gun was in the order of supersonic to twice this speed. For the HA coating it was decided to use a standard powder that conformed to ISO 13779-1,-2,-3 and -4, the

results of the trials showed that it was possible to generate a coating of Ti and HA or just HA on the surface of the cup. It was also possible to generate a coating thickness the same as can be found on conventional cups of around 75µm and surface roughness of approximately Ra 59.6µm.

Selection of dual coating process parameters

Several test samples were manufactured these consisted of tensile test samples (standard dog bone shaped) which were coated with both HA and Ti HA following the grit blasting process. The result of the preliminary trails showed that it was possible to coat the samples with both HA and Ti HA and that the adhesion to the samples was good however the process distorted the samples and following the process the samples had bent by up to 2 to 3 mm. Modifications were made to the process and further trails were performed, the results of these trials were successful and produced samples with no distortion.

Following several coating experiments involving Ti and HA in different combination to determine if a Ti coating was needed or if it was possible to just have a HA coating on the back of the cup. It was determined that in order to obtain an adhesion of the coating to the cup and for the surgeon to be able to identify the cup position (post operation) it was decided to have both a Ti and HA coating on the cup. In the first instance a thin Ti coating (30µm) was applied with a 70µm HA coating.

To make the cup more prominent against both soft tissue and bone the Ti coating was increased around the equator for approximately 10mm from 30µm to 70µm. It was decided to only increase the coating in this rejoin so as to prevent the fins from becoming clogged with the coating media.

Work Package 5 - Development of clinical instrumentation for new generation implant materials

Work comprised of designing and developing the alignment instruments and impaction cap needed during the insertion procedure. Following the design of the acetabulum cup a series of designs for the alignment instrumentation were generated. However following feedback from the surgeon group the final design of the alignment instrument was determined and consisted of a device that located in the reamed acetabulum with a location arm that hooked on the ischia spine of the pelvis. Once in position this would allow the location hole for the acetabulum cup to be drilled.

In order to impact the cup in the acetabulum a series of designs for the impaction cap were generated. The main criterion for the impaction cap was that it fully supported the cup during the implantation procedure thus reducing the possibility of distortion to the CF-PEEK cup. A final design for the impaction cap was generated which gave full support to the cup while locating in the holes at the bottom of the horseshoe. A collet design with a central locking pin holds the cap to the cup. The collet fits into the hole which has the reverse taper to that of the collet and once the locking pin is inserted which open the collet locking the two components together.

Trials with both the alignment instrumentation and the impaction cap were performed both in the laboratory and by a surgeon during the cadaver trials. The results of these test showed that the alignment instrument was able to position the cup in the optimum position to allow for the best range of movement. The result of the testing performed with the impaction cap showed that it held the cup firmly during the impaction procedure and allowed the cup to be fitted into the acetabulum without distortion. The impaction cap also permitted the removal of the cup from the acetabulum.

Clinical Instrument Development

Following an in-depth study of the instrumentation used for the current implantation of the ADEPT resurfacing implant it was decided that new instrumentation would not be required for the implantation of the new femoral component as this was similar in design. Only slight modifications to the existing instrumentation were needed in order to fit the femoral components. The main problem was with the development of the acetabulum cup instrumentation; this required the development of a location device that would allow the surgeon to fit the cup in precisely the correct position first time. This was based on the knowledge that once impacted in place it would not be possible to realign the cup without compromising the initial fixation. Therefore it was decided to incorporate location pins on the back of the cup which would fit into template pre-drilled holes in the pelvis. The second technical challenge was that of location and support of the cup during the implantation process. To prevent damage to the relatively compliant cup during the implantation process the cup requires a large area of contact with the impaction cap.

The impaction cap was therefore designed to conform to the same geometry as the internal surface of the cup which not only prevented damage but also ensured that no distortion would occur during impaction. The final obstacle to overcome was that of location of the cup and cap to allow the surgeon to manipulate the cup during the insertion process, following several design concept brainstorms and prototype modelling it was decided to use the hole in the bottom of the acetabulum cup for this purpose. Following the design of this new cap several rapid prototypes were made for analysis and with some final minor adjustments the finished design was determined and prototypes were manufactured.

Following consultations with a surgeon on the design of the cup it was decided to remove the 3 location pins from the back of the cup as there were concerns that one or more of these could protrude through the back of the pelvis if the cup was positioned poorly during surgery. Therefore a new location feature was designed for the back of the cup which would eliminate this possibility. The new location feature consisted of a single longer stem (pin) that protrudes down the centre of the iliac spine (see Figure 10)

The new cup location design meant that a new design for the instrumentation was needed, therefore a design was produced where the alignment instrument locates in the reamed acetabulum but also fixes around the back of the pelvis onto the ishia spine.

Design of the Impaction Cap

In order to impact the new cup in the acetabulum a new impaction cap was needed as methods used for metallic cups were unsuitable for the PEEK. Therefore a series of designs for fixing the impaction cap to the cup were generated. These looked at attaching the impaction cap to the cup through the hole in the bottom of the cup. With this design once the correct position has been achieved the pin is pulled allowing for the cap to be removed.

Following the development of the impaction cap, prototype caps were manufactured for test and analysis. Following the manufacture of the prototype components injection moulded cup were attached to the impaction caps and implanted into cadavers to test the system.

Work Package 6: Mechanical testing and surface analysis

During this work package a number of physical tests and simulations were developed for the verification of the design and material integrity of the femoral and acetabular components. In order to conduct the work, a number of key factors were examined:

-The mechanical strength of the ceramic components under in-vivo loading

-The geometric conformity of the acetabular components after implantation,

-The dynamic friction in the bearing between femoral and acetabular components,

-The predicted tribological conditions in the bearing couple,

-The loads experienced by femoral and acetabular components under surgical loading,

-The loads required to remove the acetabular cup when implanted, and

-The resistance to lever-out loads of the acetabular cup when implanted.

Ceramic component testing

Physical testing of representative prototype ceramic heads was conducted using worst case support and implant positioning for three main stress concentrations identified under in-vivo loading, as reported and simulated in Work Package 2. The heads were loaded in servo-hydraulic test machines, and the fracture load recorded.

RESULTS

The heads were required to sustain in excess of 16kN axial burst loading. Two heads sustained 50kN without fracture, and the third fractured above 47kN. The stems were required to sustain in excess of 1.27kN, and sustained a minimum of 3.38kN. The heads were required to sustain in excess of 5.6kN axial load, and sustained a minimum of 13.73kN.

Geometric evaluation of the femoral components.

Uncoated and coated cups were implanted into a range of under-reamed hemispherical bores in representative foam biomechanical test material (Figure 18).

The cup deformation was measured, and the resulting frictional torque generated in internal-external rotation articulation was recorded.

Further tests were conducted for the bearings using full gait and stair climbing / descent loading cycles, incorporating flexion-extension and internal-external rotation articulations. This was conducted with a novel test platform incorporating a multi-axis robot to apply the required load magnitude and direction cycles, taken from the literature.

Side loading tests to evaluate the effect of incorrect fitting.

Tests and computational analyses were conducted to consider the influence of cup malpositioning upon the integrity of the implant-bone interface and the bearing performance.

First, a test was conducted where cups were pressed-in to representative foam blocks. The cups were then levered out by applying force on the cup rim, representing an impingement load in-vivo, as a result of cup-femoral neck impingement contact, which would be a possibility if the cup were malpositioned.

Second, a finite element analysis was conducted to predict the tribological conditions in the cup and the proximity of the contact patch in the bearing to the edge of the cup's bearing surface. Edge loading on the hemispherical part of the bearing surface would be no different than for currently used sub-hemispherical resurfacing cups, but the novel aspect of this cup, without clinical precedence, was the bearing surface cut-out, so this was the focus of the investigation. The cup was oriented with relatively steep abduction according to current surgical recommendations, and extreme anterior axial rotation. Then the contact patch location was predicted simply with CAD geometric analysis, and the contact pressure was predicted in more detail with a Finite Element (FE) analysis model. This was conducted for load cases representing normal gait, stair ascent and descent, and deep-flexion rising from seated. The peak joint contact force instant of each cycle was applied in quasi-static models. Analyses were run for the same range of bearing clearances tested previously (250um, 500um and 750um). The peak stress in the cup was also predicted in these scenarios, to support Work Package 2's prior cup strength analysis.

RESULTS

In physical testing, average torques of 16Nm to 34Nm were required to lever the cup out of its supporting foam block, with the lever-out torque increasing with a greater interference fit between the bone and the cup. The lever out resistance was found to be considerably lower when uncoated cups were tested.

In the CAD analysis, the contact patch was predicted to lie within the bearing surface for gait and stair ascent/descent activities. However, in the deep flexion 'rising from seated' load case, the contact patch was predicted to reach the edge of the acetabular notch in the bearing surface.

The peak contact pressure predicted was 21.6MPa in stair ascent, when the bearing clearance was largest (750um). The contact patch was predicted to reach the edge of the bearing surface during rising from seated when the patch was largest (250um clearance), but owing to the lower magnitude of the joint contact force in this case, the pressure was not expected to exceed 9.3MPa, which was lower than the peak contact pressure for the stair descent load case.

A combined computational modelling study and physical test programme was conducted to assess the strength of the femoral head implant under surgical impaction loading. A prototype head prosthesis was cemented onto a representative shape and stiffness foam biomechanical test material cylinder, and attached to a load cell. A head impactor instrument used in current resurfacing surgery was obtained, and modified to feature a slide hammer.

The force-time characteristic of the impact, and the calculated cumulative impulse over time, were analysed in comparison to the FE model results, for model validation. Two models had been produced, including and excluding the mass and stiffness influence of the surgeon's hand, holding the impactor. Ten impact loads were required to verify the head's strength against impaction loads.

RESULTS

During the tests, the head was impacted ten times without fracture.The force-time characteristic recorded in the physical tests and the calculated cumulative impulse both showed good correlation with both basic and hand-damped FE models in terms of peak force and duration. The basic (undamped) model over-predicted the peak force by 49%, but agreed closely with the cumulative impulse. The hand-damped model only over-estimated the peak force by 23% but underestimated the cumulative impulse by 16%, so the basic model was selected as a worst-case.

Work Package 7: Tribological and geometry study

Work Package 7 aimed to 'optimise the wear and friction performance' of the prosthesis components. Deliverables were:

-To provide details for the wear and friction systems and methods ready for tribological testing, and

-To derive the optimal geometry for the ceramic on polymer bearing surfaces with respect to their tribological performance.

Two main approaches were used to assess the design's tribological characteristics:

-Finite element analysis of the contacting bodies, coupled with theoretical contact calculations, and

-Wear testing using a 10-station ProSim hip wear simulator.

The theoretical calculations were used to predict the performance of three bearing clearance options for the proposed BIOLOX delta ceramic on Carbon Fibre Reinforced PEEK (CFRPEEK) prosthesis. Then, the wear simulator testing was conducted to assess the performance of the preferred design relative to two traditional bearing couples: ceramic on ultra-high molecular weight polyethylene (UHMWPE) and ceramic on Highly Cross Linked Polyethylene (HXLPE).

The theoretical predictions indicated that the ENDURE bearing is likely to operate in a boundary lubrication regime, and literature review showed that this is consistent with typically employed bearing clearances with this material combination, which are insufficient to achieve fluid film lubrication. The literature also indicates that friction factor in similar ceramic-CF-PEEK bearings is independent of clearance, provided the clearance is above 250μm. Therefore the design clearance must be sufficient that implantation and service deformations do not reduce the in-vivo clearance to below this level.

FE indicated that the deformation under normal service loading is likely to be small in comparison to the bearing clearance. Deformation under press-fitted implantation is likely to be higher, and should be the focus of further research.

Finally, wear testing results for simple hemispherical total hip replacement cups of the correct material combination and clearance were obtained which showed no significant difference in wear between CFRPEEK cups and XLPE cups representative of those in clinical use. For this work package we have combined the tasks 7.1 Established testing systems, 7.2 Literature search and review of similar designs and testing methods and task 7.3 Wear simulation testing in to one report that outlines all of the work performed as these task were so closely related.

Hard-on-soft hip replacement bearings (principally metal-on-ultra-high-molecular-weight-polyethylene (UHMWPE)) have been seen to function well up to 25 years in-vivo [1]. However, the use of this bearing combination is unsuitable for younger patients and resurfacing. For patients below the age of 50 years the survivorship rate is only 79.3% at 11 years. This is due to the patient's increased activity levels, resulting higher loads and greater number of cycles experienced by the implants adding to the chances of revision surgery. Osteolysis, the body's immune response to polyethylene wear formed through local mechanical damage on the contact surface has been suggested as the major contributing factor to the failure of total hip replacements. Wear particles are generated due to articulating mixed / boundary lubricated contact between the bearing surfaces. In order to reduce the incidence of osteolysis the wear properties of the artificial joint need to be improved to reduce the volume and bioactivity of the wear debris generated.

Hard-on-hard (metal-on-metal (MoM) or ceramic-on-ceramic (CoC)) bearings were introduced to encourage fluid film lubrication, in which the load is fully supported by a lubricating film, eliminating contact between the bearing surfaces to extend the lifetime of the prosthesis. Nevertheless achieving fluid film lubrication in a MoM bearing is not instantaneous and involves an initial 'running-in' period in which wear rate is high. The film formation mechanism begins when the MoM components are in relative motion and are loaded. At first implantation, a full lubricant film cannot develop due to small polar bearing

point contact between the new head and cup surfaces . Postoperative activities result in wear occurring at a high rate and the area of contact between the surfaces increases. This 'running in' phase ends when the clearance in the contact patch reduces towards zero and the geometry is most favourable for fluid-film lubrication . As migration into the 'steady state' phase occurs and the wear rate slows the contact patch continues to develop at a reduced rate. The effective clearance within the contact patch and within the surrounding entraining geometry is then slowly consumed by wear. Although the wear rate during the steady state is low there is concern over the initial high running in wear, releasing metal ions which are dispersed leading to systemic exposure, and potentially have a negative effect on the patient's health.

A recent approach to improve the success of a joint prosthesis is to improve the wear resistance and mechanical properties of the acetabular cup material. Carbon fibre polyetheretherketone (CFRPEEK) has been suggested as a potential bearing material due to its high wear resistance and mechanical properties which will allow the material to function alone in an acetabular component without the requirement for a metal backing shell for support. In addition, PEEK's proven biocompatibility indicates long term use without an adverse reaction in-vivo due to the material's excellent chemical stability which is a particular problem associated with the wear debris produced by UHMWPE and metal cups. Wang et al. (1999) carried out an investigation into the influence of carbon fibre content and wear resistance. The study concluded that PEEK resin blended with 30 w/w% of PITCH carbon fibre gives the optimal wear resistance, five times lower than 10% reinforcement and three times lower if 50% reinforcement was used.

Pin on plate studies have shown a combination of CFRPEEK and ceramic exhibits a five times reduction in wear factor compared to UHMWPE and CoCrMo combinations. Unlike, hip simulators pin on plate experiments do not replicate the conditions in-vivo. Instead the test is useful as a material screening technique to compare new potential materials.

To gain a greater understanding of wear rates of PEEK in a set up that more closely simulates the hip motion and loads through the components, hip simulator studies have been performed. The first hip simulator results were reported by researchers from Howmedica who performed an investigation on injection moulded 30% discontinuous pitch carbon fibre PEEK acetabular cups articulating against zirconia heads. The CFRPEEK combination exhibited two orders of magnitude less wear than the ceramic-UHMWPE combination after 10 million cycles.

Materials and Methods

Test 1: Theoretical Analysis and Modelling

Wear test evidence from the literature indicates that CF-PEEK cup prostheses will operate in mixed-boundary lubrication. The following is an analysis of the contact conditions in the proposed ENDURE cup, aiming to identify a target clearance, contributing to the detailed design. This study employed theoretical predictions and an FE analysis model. Three 48mm diameter cups were analysed: the nominal cup as drawn (clearance 750µm), plus variants with 500µm and 250µm. The contact pressure distribution and patch location was predicted under loads representing gait, stair ascent, stair descent and rising from seated, summarised in

The FE model from Work Package 6 Report 1 was re-used for this analysis, based on the ENDURE cup set in a cylindrical block of PMMA and loaded with a rigid spherical head.

Considering micro-Elastohydrodynamic Lubrication (uEHL), formulae from Hamrock and Dowson were employed to predict the lubricant film thickness 'hmin' in spherical-spherical bearings and to calculate the lambda ratio of the loaded bearing which indicates its likely lubrication regime. The lambda ratio compares the lubricant film thickness to the maximum surface roughness. A lambda ratio above 3 implies the achievement of fluid film lubrication, below 1 implies boundary lubrication and between 1 and 3 indicates a mixed lubrication regime. These formulae were input into an Excel spreadsheet and verified using example results given by Dowson.

The approach used in this study was to predict the minimum film thickness for several bearing clearances for the full size range of ENDURE cups, using the same service loading from the Dowson paper. The surface roughness of the CF-PEEK injection mouldings was not known at the time of writing. Therefore, with a surface roughness for the ceramic estimated as Ra=20nm (range 7nm - 50nm for ceramic femoral heads in general), the equations were used to predict the threshold CF-PEEK surface roughness values to produce boundary or fluid film lubrication regimes.

With the uEHL calculation predictions, the results parameter was the maximum CF-PEEK roughness to permit mixed or fluid film lubrication under gait loading, across the full ENDURE size range. With the FE Model, the main output parameters were the peak contact pressure and the radial deformation of the cup rim, indicating the additional clearance required in the unimplanted prosthesis. This was calculated as the designed rim diameter minus the diameter of the maximum inscribed circle (MIC) fitted to the rim of the loaded, deformed cup. The MIC diameter was calculated using an algorithm written into a post--processing subroutine, which performed similar measurements to roundness testing machines.

Test 2: Physical Wear Testing

To assess the suitability of CFRPEEK as an acetabular component material and assess a few of the conditions described previously, long term wear tests were performed on pitch-based CFRPEEK cups articulating against BIOLOX Delta alumina femoral heads. Identical HXLPE and UHMWPE acetabular cups articulating against BIOLOX Delta alumina femoral heads were also tested for comparison.

The wear samples were nominal diameter 36 mm hip prostheses of BIOLOX Delta ceramic (CeramTec GmbH, Germany) heads against acetabular cups of 3 different materials – CFRPEEK (Invibio Ltd, UK), UHMWPE and HXLPE. Testing samples included 4 CFRPEEK, 3 UHMWPE and 3 HXLPE cups and were soaked in deionized water for a minimum 6 weeks before the wear test.

Station	1	2	3	4	5	6	7	8	9	10
Cup	CFRPEEK 1	HXLPE 2	UHMWPE 1	CFRPEEK 3	HXLPE 1	UHMWPE 3	CFRPEEK 2	HXLPE 3	UHMWPE 2	CFRPEEK 4

The test was carried out according to ISO14242 with the following conditions:

-Load: 50 - 3000 N single axis twin peak Paul type load curve

-Movement: ±10° internal/external and -15° to +30° extension/flexion

-Frequency: 1 Hz

-The cups were installed with an inclination angle of 35° in the medial-lateral plane and a single dynamic force was applied along the vertical axis.

-Fluid: 25% newborn calf serum with 0.1% sodium azide

-The test was carried out for 5 million cycles

-The solution was changed at least every 0.5 million cycles

-Interruptions were made at 0.5, 1, 2, 3, 4 and 5 million cycles for gravimetric determination of the wear and worn surface analysis

-Prior to the gravimetric measurement of wear, components were washed in detergent water, thoroughly rinsed in water and deionized water, cleaned in alcohol using an ultrasonic bath for at least 10 minutes to ensure removal of all traces of debris and lubricant, and then left in an atmosphere controlled room for at least 24 h to dry and thermally stabilize

-Wear was determined gravimetrically using an electronic balance (Sartorius ME235S, Germany) to a precision of 0.01 mg

-The gravimetrical wear was converted into geometrical wear using specific density of 1.41 for CFRPEEK, 0.934 for UHMWPE and HXLPE, and 4.36 for Biolox Delta ceramic

-The worn surfaces were analysed using the Alicona InfiniteFocus 3D optical microscope.

Results and Discussion

Micro-Elasto-Hydrodynamic (µEHL) Equation Results

µEHL calculations led to the prediction of minimum CF-PEEK Ra roughness values to permit mixed and fluid film lubrication regimes to be achieved. These show that for the full size range, mixed lubrication should be achievable with Ra values of 32.9nm, 48.3nm and 86.6nm for the 250µm, 500µm and 750µm clearance cups respectively. Due to its smallest equivalent radius, the lowest film thickness was generated in the smallest size. Fluid film lubrication was predicted to be achievable with an Ra value of 21.8nm for the 250µm clearance cup. FFL would not be achievable for the smaller cups in the size range with clearances of 500µm and 750µm, because the 20nm Ra roughness of the ceramic would take up a sufficient proportion of the lubricant film thickness that separation of the surfaces would not be possible.

Scholes et al measured the roughness of the CFR-PEEK MITCH cup during 25 million wear cycles. The initial Ra was approximately 3300nm, and reduced to approximately 393nm after the wear test. If these roughnesses are typical of what can be achieved in manufacturing of the ENDURE cup, Boundary Lubrication is to be expected.

Recent literature studies have reported that clinically used ceramic-on-CF-PEEK bearing couples (MITCH) typically operate in Boundary or Mixed Lubrication regimes, so the failure to achieve FFL may not be of concern. The MITCH cup, which this literature data refers to, had a larger nominal diametric clearance (0.80 - 0.91µm) but greater ability to deform with its full cut-out horseshoe shape. The wear simulator data reported would probably not include the deformation resulting from press-fitting, so represents a worse case (high clearance). Older literature studies from the MITCH development process tested lower clearances and saw high friction with zero clearance, but no influence of clearance on friction for clearances between 250µm and 750µm.

The implication is that in the fully hemispherical, less flexible ENDURE design, the selection of bearing design clearance should be informed by prevention of cup clamping, reducing in-vivo clearance to zero.

Work Package 8 - Sterilisation and Biocompatibility

This work package addresses the serialisation, packaging and biocompatibility of the new hip components and the instrumentation needed for its insertion. During this work package a review of the materials to be used in the construction of both the femoral and acetabulum components was performed. Following a literature review it is clear that the materials selected for the implants have already history in the medical field in similar applications and therefore problems with the sterilisation and biocompatibility were considered to be low risk. As part of the work performed the materials to be used and the possible configuration of the coatings to be applied was identified. Having identified the materials to be used a list of tests that would be needed in order to ascertain the biocompatibility was generated. Another key part of this work package was the development of handling and packaging protocols to allow the final products to be assembled where necessary and packaged in a form the was both cost effective and easy to serialise.

The first challenge was to establish a final cleaning process for the ENDURE implant system. Using years of prior experience with similar devices; Hunt elected to process the devices within an ISO Class 6 (Class 1000) cleanroom. Having inspected the devices, Hunt would utilise a state of the art aqueous multi-frequency ultrasonic cleaning system; followed by final disinfection and sterile filtered forced air drying.

The final cleaning process was required to consistently remove upstream manufacturing contaminants for the pre-sterilized components. By using state of the art ultrasonic cleaning, in hand with well understood cleaning/rinsing solutions, Hunt was able to process devices at their optimum level of pre-sterilization cleanliness, minimising risks associated with upstream contaminants, such as residual particulates and processing media.

Once the cleaning process was realised, Hunt focussed upon determining a sterile barrier packaging system, that would be designed to address a requirement to support the medical device within it's packaging; in such a way as to minimise contact between the packaging and coated surfaces, known from other medical devices to be easily damaged in transit if not fully considered at the design stage. Hunt designed and prototyped a 3 x stage blister packaging system, that 'suspended' the coated side of the device in atmosphere, out of contact with the packaging materials. This design not only prevented damage to the Implant; but also associated damage to the sterile barrier packaging system.

Having determined the cleaning and packaging method for the ENDURE implant system, Hunt considered a variety of sterilization methods, taking into account the material requirements and the associated risks of utilising a sterilization process which may affect the efficacy of the implant itself. Having reviewed the materials and established that Gamma

Irradiation was likely to be the most appropriate sterilization method available; Hunt Gamma Irradiated a range of samples used for clinical study and cytotoxicity. Gamma Irradiation was shown to be effective in providing the required dose (25-35kGy) and subsequent testing demonstrated that the device functioned as design intended, regardless of irradiation.

Having provided a clean, packaged, sterile device; Hunt supplied samples for other studies; including some Biocompatibility testing. Biocompatibility testing undertaken by Biomatech, demonstrated that the finished devices were not harmful to cells and showed great promise for additional testing of devices manufactured via the final manufacturing supply chain.

Work Package 9: Cadaver trials

During work package 9 two cadaver trials were performed to validate the instrumentation and hip components developed during the course of the project. The cadaver trials were performed at Newcastle surgical training centre. Two cadavers were prepared and the surgeon performed the implantations using the posterior approach.

Once he had cut through the soft tissue he dislocated the hip exposing the femoral head and acetabulum of the pelvis. He then measured the femoral head using the gauges supplied in the surgical kit to determine that the prototype cup supplied would fit the femur. Once he was satisfied that the cadaver would be suitable for the operation he drilled a hole for the location pin and fitted the pin. Once this was done he trimmed the head using the cylindrical cutter provided and then trimmed off the top of the head to give a cylinder shape to the head. Following the chamfering of the head to give clearance on the inside of the resurfacing head he impacted the ceramic head onto the femur until it was fully seated.

Having successfully implanted the femoral resurfacing head the surgeon turned his attention to the acetabulum which he reamed to a depth then opened up using sequentially larger diameter reamers until he had reached the optimum size for the cup to be fitted. Following the reaming of the acetabulum the drill guide for the creation of the location hole was inserted in to the reamed acetabulum with the location arm hooking round the ishial spine on the back of the pelvis. Once the drill guide had been located properly the location hole for the acetabulum cup was drilled. The drill guide was then removed and the acetabulum was cleaned of all debris. The impaction cap and cup assembly was attached to the impaction handle and the location pin on the back of the cup was aligned with the pre drilled hole. Then impacted the cup into the acetabulum until it was fully seated, once this was done he removed the impaction handle and pulled the pin on the impaction cap releasing it from the cup. He then reconnected the hip and manipulated the cadaver's leg to ensure that the optimum range of movement had been achieved.

Following the operation he gave feedback as to the ease of the operation and made recommendations on the instrumentation used. He stated that the new instrumentation and prosthesis implants had been easy to fit, but would recommend that the angle of the impaction handle location on the impaction cap be realigned in line with the location pin.

Task 9.1 Cadaver Trials

Objective: To ensure that the implant and instrumentation are effective on implantation, realignment and will facilitate successful retrieval of the femoral components. The must also demonstrate their ability to sustain the loads generated during surgery and achieve the desired implant alignment.

To validate the new hip components and the instrumentation for their implantation two cadavers were obtain and hip surgery was performed on the left hip of both cadavers. The surgical procedure was performed at Newcastle surgical training centre. Both during the implantation procedure and following the operation the surgeon gave feedback on the hip components and the ease of use of the instrumentation. The feedback from surgeon was positive for both the femoral and acetabulum procedures, he stated that the femoral component was similar to the exciting procedure and as such gave good location and alignment of the resurfacing head on the femur. With respect to the acetabulum cup implantation he stated that once reamed the alignment aid was east to install and use. With respect to the impaction cap and cup as these fitted to conventional impaction handles the use of these was simple his only comment was that the impaction alignment would be better if it followed the direction of the location pin. Once impacted he found the removal of the cap from the cup simple and the hole at the bottom of the cup allowed him to ensure that the cup was fully seated. This report shows photographs taken during the procedure and explains in more depth the process steps used for the implantation.

Work Package 10: Detailed design

The aim of this work package is to define the final design of the resurfacing femoral head and acetabular cup components. Within this remit, the surface finish, geometry and mechanical properties of the components are established. This report reviews the design development and manufacturing process of the components based on underpinning finite element (FE) analyses and verified with physical tests.

Following a comprehensive literature search for both the femoral head and acetabulum materials currently used in hip components and after an evaluation of the mechanical properties and manufacturability, BIOLOX (femoral head) and CFRPEEK (acetabular cup) were selected.

In order to combine a ceramic head structure and cementless fixation, the fixation geometry and wall section thickness profile of the head were both modified, to incorporate a rough titanium/hydroxyapatite coating to achieve biological fixation. The design was verified fundamentally in an in-vivo representative FE model, implanted on a replica femur, and this supported the fundamental design philosophy in terms of the stress in the prosthesis and the strain in the supporting bone. The in-vivo FE model also supported the incorporation of stiff ceramic material, which has been proposed and could lead to additional stress shielding in comparison to metal implants. The model indicated that with incorporation of a shortened metaphyseal stem design in comparison to currently clinically used metal resurfacing head designs, the net increase in stress shielded bone volume could be minimised.

Having generated basic prototype designs, FE models were generated to verify each of the components. These models reviewed the stresses generated within each component both during normal gait movement and under stumbling loads. The analysis indicated that the ENDURE head would experience between 143 and 305 MPa, which it should withstand safely, indicating a safety factor of 3.8 compared to the characteristic flexural strength of the material. The models also investigated the bone interface conditions. The interface analysis showed that there was frictional contact on the superior side of the prosthesis-bone interface, while there was a gap opening on the inferior side. The highest tangential micromotion (sliding) was 35.9 µm, located at the boundary between contacting and open areas of the interface. The highest normal (opening) micromotion was 20.2 µm, at the inferior edge of the interface. The literature review highlighted that bone in-growth can be achieved for small extents of micromotion (in the range 20-56 µm), however, motions in excess of this value can result in no bone growth and the formation of fibrous interfacial tissue. This indicates that on the basis of mechanical factors alone, the whole cementless interface surface could be capable of achieving fixation through bone in-growth.

As part of the preclinical analysis process for the proposed ENDURE resurfacing head, mechanical tests were required with load cases and pass criteria to represent the extremes of in-vivo loading. These tests consisted of:

-A stem test to evaluate the bending stress generated at the root of the stem during in-vivo loading.

-A hoop tension test to evaluate the strength of the head's shell under worst-case implant mal-positioning, as in order to achieve a prosthesis with a patient sizing equivalent to traditional metal resurfacing heads, a ceramic head design will feature a thin rim which will undergo hoop stress during implantation and in service,

-An ultimate strength test, to evaluate the burst strength of the whole head with correct positioning, and

-An interface torque test which was designed to determine the strength of the prosthesis bone interface under worst case loading conditions, where the torque axis aligns with the head axis.

FE analysis of the stem strength test indicated that with a pessimistic estimated material strength, the full size range of heads would sustain between 1.99 and 2.14 kN applied directly to the stem tip (size 58 and size 40 mm heads, respectively). Physical testing of two mid-size heads (48 mm) demonstrated strength over 3.3 kN, giving a minimum safety factor of 2.66 compared to the 1.27kN pass criterion, from the clinically successful BHR implant. Whilst the pass criterion force may seem low in comparison to 9x bodyweight traumatic loads in-vivo (approximately 8 kN, Bergmann et al [3]), this test represents very much a worst case of stem load application (directly on the stem tip), which is more extreme than could be generated in a correctly implanted and supported prosthesis. Some stem loading would occur as a distributed load along the stem-bone interface, generating a stress concentration at the stem root. However, the shell of the implant would sustain a large percentage of the load, so the stem root would only see a fraction of the total joint contact force. Predicted stem root stresses under physiological loads are small in comparison to those predicted in this study, so the 1.2 7kN pass criterion is justified as representing an extreme case, so the test results indicated that the current ENDURE prototype design would have sufficient prosthesis stem mechanical strength.

For the hoop testing, a mechanical test was designed during the project, whereby the head is oriented with its axis horizontal without any bony support, and loaded with an acetabular cup. The physical test setup represented a worst case of varus prosthesis orientation, loading and poor prosthesis support. The pass criterion was defined as 5.6 kN, the yield load of the clinically successful metal BHR implant. The results of this FE analysis predicted that under 5.6 kN, the ENDURE design would have peak stress concentrations of 411-416 MPa (size 40 mm) and 269-325 MPa (size 58 mm), both at the shell rim. Again, using a pessimistic estimate of the material strength, the heads were predicted to have a minimum fracture load of 5.7kN (40 mm) and 7.3kN (58 mm). In physical testing, the mid-size (48 mm) heads demonstrated crush loads of over 13.7 kN, giving a safety factor of over 2.5 compared to the pass criterion. The results of this test suggested that that the head would meet the design criteria for wall rim strength under worst case crush loading.

The head/femur interface torque test was designed to determine the ultimate strength of the prosthesis-bone interface under worst-case loading, where the torque axis aligns with the head axis. As such, the prosthesis has minimal geometric stability from the corners of the prepared chamfered cylindrical femoral head, and is only fixed by the shear strength of the interface. This mechanical test was designed, whereby the head is implanted on a sawbone stub, oriented with its axis vertical, and loaded in torsion with a bonded acetabular cup and a torque wrench. The pass criterion was defined as 10 Nm according to prior test

protocols. This mechanical test setup was analysed computationally, to assess the shear strength of the ENDURE prototype head design's fixation. The results of the test showed that under a 10 Nm torque loading the peak interface shear stress was 2.74 MPa for the 40mm head and 0.98 MPa for the 58 mm head. Prior testing indicated shear strength of the ceramic-coating interface of 35MPa, indicating that even if this torque is not supported over the full interface area, the proposed design would have sufficient interface strength to support the worst-case (magnitude and direction) 10Nm torque without coating delamination.

The inclined loading test was designed to determine the ultimate strength of the prosthesis with normal orientation and simulated support, where the head is oriented with its axis at 45° to horizontal, and loaded with an acetabular cup. The pass criterion for this test was 16kN load, representing a peak stumbling force and a safety factor load multiple of 2. FE analysis of this test indicated peak stresses of 256 MPa (size 40 head) and 161 MPa (size 58 head), indicating a minimum fracture load of 25 kN (size 40 head) and 42 kN (size 58 head) using a pessimistic material strength estimate. In physical testing, size 48 mm heads sustained a minimum of 47 kN before bulk fracture, giving a safety factor of 3 compared to the pass criterion. This provides additional evidence to suggest that the shell of the basic prototype ENDURE head design is likely to be sufficiently strong to support extreme cases of loading with physiologically representative load directions and support.

Utilising all of the information generated during the course of the tests performed a final design of the femoral head was achieved.

Acetabulum Cup testing and final design

Following the literature search on current materials used for the manufacture of hip components the following aspects were considered when looking for a suitable material for the acetabulum cup. These include strength, stiffness and wear resistance with the overall aim being that the material must enable a component to be manufactured which was biomechanically compliant and intended to reproduce the healthy joint's function.

To enable us to do this we performed an investigation into possible materials applicable for an acetabular cup including cobalt chrome, Ultra High Molecular Weight Polyethylene (UHMWPE), PEEK OPTIMA and CF-PEEK MOTIS. It was concluded that CF-PEEK possessed the most favourable characteristics for the ENDURE acetabular component.

The literature search for current cup designs showed that there are three main types, a metal cup with an UHMWPE designed and fitted successfully in elderly patients with low

activity levels. Metal on metal or metal on ceramic bearing surfaces were introduced to reduce the incidence of implant failure by reducing the number of wear particles produced. However the main problem with the larger metal cups include the raised concerns over the high concentration of cobalt and chromium ions measured in the serum of patients.

Previous acetabulum designs have employed CF-PEEK, specifically the Cambridge cup and its second generation design the MITCH cup. The Cambridge cup the first acetabular cup to be produced using a 3.0mm UHMWPE insert with a 1.5mm thick backing made of a type of PEEK called polybutyleneterephthalate (PBT) which was reinforced with 30% carbon fibre. It is manufactured to a horseshoe shape which is intended to replace the load bearing hyaline cartilage and subchondral bone of the acetabulum. The stiffness of the PBT layer enabled the cup to deform with the surrounding acetabular bone when it was loaded. Hydroxyapatite (HA) was plasma sprayed onto the outer surface to further improve fixation to the subchondral bone. However the cup suffered from a migration problem which was accredited to the design's inability to achieve an adequate press fit.

In normal THA prosthesis the range of motion is maximised through the use of a large head diameter and a small neck diameter which enhances the hip performance by allowing greater range of motion before component impingement. It is known that hip resurfacing decreases the head to neck ratio as the femoral neck is retained. Impingement can occur when the retained femoral neck abuts against the acetabular component or anterior acetabular bony wall. This can be painful and restrict motion. ISO standard 21535 states that 100° flexion/extension; 60° abduction/adduction and 90° internal/external rotation is required. However, even the earliest literature states that a greater range of motion needs to be achieved in order to allow everyday tasks to be performed. Johnson and Smidt (1969) and Roach and Miles (1991) have shown flexion/extension values in the range of 125-135° which is higher than the standard's value. Clearly if THA implants are designed to this specification, the patient's post operative ROM will be limited. Kluess et al. (2008) performed a study on how the implant designs affect the flexion/extension and internal and external rotation angles that are achievable.

Total Hip Replacement commonly have a higher range of motion which appears unnecessary as it is not fully utilised, but it does provide a large safety margin with respect to mal-positioned components. A surgeon could place the acetabular component within 15º of the target values and the patient would still exhibit full ROM without impingement. This safety factor is removed with the resurfacing components as the available ROM is much closer to that required by the patient especially in flexion/extension. Resurfacing components therefore require more precise positioning of the acetabular component to allow full ROM without impingement in flexion/extension. Although resurfacings provided little extra ROM in flexion/extension, they all facilitated more ROM in abduction/adduction than necessary. It is important to increase the range of motion of a resurfaced replacement to enable a

greater ROM to be achieved specifically flexion/extension. This can be done in a number of ways which include increasing the head size or making the cup a different shape to the standard hemisphere. Other areas of improvement can be the inclusion of a lip on the outer rim and increasing the flexibility of the cup through choice of material. Each design idea has advantages and disadvantages.

The design ideas discussed in this project include:

1.Development of a new bearing couple: Ceramic on CF-PEEK

2.Lower Profile Cup / Rim Cut outs: Increasing the edge angle of the cup by removing rim material

3.Offsetting the bearing surface

4.Anatomical Cup: Depressed horseshoe section on differing thickness bearing surface.

5.Cup Rim Lip

6.Updated surgical instrument design to improve positioning

Following a review of all of these ideas it was decided that in order to achieve the ROM required by the ISO Standard No.21535 the bearing surface, the depressed horseshoe design provided the stability of a cup joint with a reduced thickness due to the CF-PEEK material properties. It was a novel idea but not so extreme as other so called 'anatomical' designs, however the ROM was still below the required value. It was decided that the offset design looks the most promising due to the patent not restricting the idea and the soft tissue interaction being reduced through careful design. The horseshoe design could be used in conjunction with the offset to produce a cup that is flexible but stable with an increase ROM over current designs. When combined with the necessary surgical instrumentation designed to allow the positioning to be fixed accurately it was deemed that a range of movement dictated by ISO standards was attainable even for the resurfacing head.

Having defined the internal geometry of the cup the research focused on the external surface of the cup which had to integrate with the prepared acetabulum to generate good initial stability. Several proposed ideas were generated to provide an interlocking mechanism with the acetabulum. These included the incorporation of three location pins augmented with fins which once pressed into the acetabulum provided good initial fixation.

The cup design featured three location pins to help align it in the acetabulum. This would involve using the alignment drill guide developed during the project and would involve placing the alignment instrument in the acetabulum then trial fitting the femur in the trail

cup. Once the correct alignment has been achieved then the drill guide would be inserted into the cup and the holes drilled. However when the prototype cup samples were manufactured and trialled in the acetabulum it was found that in pelvises with poor bone stock the location pins could possibly protrude through the back. Especially when patient anatomy variation, degree of patient deformity and surgical positional inaccuracy were considered.. Therefore this idea was no longer feasible.

In order to overcome this problem a new cup design with a single tapered peg was developed together with an alignment instrument. The instrument was based on the Peter Ring implant procedure where the location pin (screw) follows the weight bearing line meaning it is not exposed to load. To locate the weight bearing line and ensure correct component positioning a specialised instrument was designed to drill a correctly oriented hole for the location pin on the outside surface of the cup. The instrument was positioned into the prepared acetabulum and a support arm was engaged around the greater sciatic notch. Once secured a hole for the peg was drilled through the instrument, in the correct location to allow the surgeon to position the cup reliably with the intended orientation.

As a result of the testing detailed in this report the final design of the femoral head and acetabular cup was established. The femoral head will be made from Biolox Delta ceramic using standard manufacturing protocols, e.g. hot isostatic pressing followed by hard machining and polishing to achieve an Ra of 0.02µm. The femoral component will consist of the short location stem capable of withstanding a 1.27kN stem tip load and a shell that will with stand a tensile stress load of 5.6kN. The inner surface of the head will be coated with a Ti and HA two layer coating with thicknesses of 30µm and 70µm respectively.

The acetabular cup will be manufactured from CF-PEEK by conventional injection moulding techniques; once moulded the hole in the bottom of the horseshoe will be drilled. The cup has been designed with the single pin location which has been offset to allow for the optimum range of movement giving a 45° abduction and 15° anteversion angle when fitted. The inner surface of the cup was produced with an Ra of 0.02µm which is similar to that of the femoral component. The back of the cup was designed to integrate with the trabecular tissue within the reamed acetabulum. The final design has location fins to assist with the location and integration of the cup. The cup has been designed to mimic the acetabulum, with the material characteristics have been developed to minimise the stress shielding under normal gait conditions. The outer surface of the cup has a dual coating consisting of a 30µm Ti layer over the whole surface with an increase in the coating around the circumference to 70µm for a width of 10mm. This was done in order to facilitate the surgeon seeing the implant through conventional X-ray or CT scanning methods. The exterior of the cup was then coated with a 70µm coating of HA to gain good early fixation with the surrounding tissue.

Work Package 11: Pre-clinical and laboratory investigation

During this work package the aim was to perform the pre-clinical testing of the implant components and evaluate the effectiveness of the prosthesis with respect to;

In vivo testing of the components to determine the amount of osteointegration that takes place during a predetermined time period

In vivo testing to determine the biocompatibility of the coating and components

In the planning of the in vitro and in vivo experiments, the biological effects of both solid and particulate materials were considered. The latter path was not judged essential by the participating partners. During work package 1-10 the following materials were selected for in vivo biocompatibility evaluation: polyetheretherketone (PEEK) grit blasted, PEEK grit blasted and coated with titanium (Ti) and hydroxyapatite (HA) plasma sprayed on the PEEK surface, Ti grit blasted with plasma sprayed Ti and HA.

All three materials were implanted in the rabbit for a time period of 6 weeks (previously known to be an accurate time point in this rabbit model for judging the early osseointegration of materials in cortical and trabecular bone). After retrieval of the intact bone-implant block, the samples were analysed with respect to bone formation capacity, cellular response to the surface and possible adverse reactions towards materials tested.

The results of the project show that Ti and HA coating significantly enhances the osseointegration and compatibility in bone of PEEK grit blasted implants. PEEK grit blasted with Ti-HA coating showed at least similar but in cortical bone even superior osseointegration compared to Ti coated with Ti-HA commonly used clinically. No adverse cellular reactions towards materials were found.

Osseointegration of the prosthetic components in total hip replacement is a prerequisite for clinical success of uncemented treatments. The osseointegration allows an effective load transfer between the prosthetic component and surrounding bone tissue. Metal components, such as Ti alloy and CoCr alloys are frequently used due to its excellent mechanical stability, however numerous disadvantages have been identified, such as wear debris, ion leakage and stress shielding. Furthermore, associated problems with clinical diagnostics and imaging using CT and MRI due to the radio-opacity.

The use of polymeric material may overcome some of these problems, where imaging technique could be used without extensive artefacts, minimizing the stress shielding by tailoring the mechanical properties in order to match the mechanical properties of the bone tissue, as well as good tribological properties. Carbon fibre reinforced polytheretherkoetone

(CFR-PEEK) has been suggested to be an attractive material for orthopaedic implant components, where the mechanical properties could be tuned by the addition of the fibres. It has been shown to be biocompatible in vitro and in vivo. However, CFR-PEEK, show inferior biological properties as compared to titanium alloy and coating techniques are required in order to improve the integration. Hydroxyapatite have been extensively used for rendering implant surfaces bioactive, using a variation of coating techniques. The most frequently used methodology in orthopaedics is plasma-spraying, with excellent long-term follow up of uncemented orthopaedic components. Further, the use of HA also allow a direct bone-implant contact at the ultrastructural level.

The aim of the current study was to evaluate the early biological response to CRF-PEEK implants, with and without a HA coating, having a HA coated titanium alloy reference as a clinical relevant control. A well-established rabbit model was used, combining both trabecular bone response and cortical bone response with six weeks healing, a suitable time-point for HA coated implants.

In summary, bone surrounding the implants was a mixture of mature lamellar bone and a woven bone close to the surface. Areas of a new bone formation with mainly osteoblasts and remodelling areas exhibiting resorption are seen. A close bone-to-coat contact was observed for the PEEK-Ti-HA and Ti-Ti-HA but not for the uncoated PEEK implants, where the soft cell-rich tissue was impede the bone formation at the contact with the surface. No adverse reactions were found in response to materials.

Bone contact

It was found less bone in contact to uncoated PEEK grit blasted surface (mean 55 ± 8 % in the femur, 25 ± 4 % in the proximal tibia and 43 ± 7% distal tibia) compared to Ti and HA coated PEEK or Ti surface independently of site the implants were placed. No differences were found between PEEK-Ti-HA and Ti-Ti-HA. Mean bone contact to PEEK-Ti-HA was: 88 ± 2% in the femur, 64 ± 8% in the proximal tibia and 69 ± 8% in the distal tibia. Mean bone contact to Ti-Ti-HA was: 86 ± 3% in the femur, 55 ± 6% in the proximal tibia and 75 ± 5% in the distal tibia.

Conclusion:

1.Ti and HA coating significantly enhances bone compatibility of PEEK grit blasted implants based on an in vivo.

2.PEEK grit blasted with Ti-HA coating showed at least similar but in cortical bone even superior bone integratiuon properties compared to well known Ti coated with Ti-HA coating.

Potential Impact:

As part of the industrial and economic validation for the ENDURE implant market analysis was performed on the potential manufacturing cost compared to the cost of manufacture and sterilisation of existing devices. The result of this analysis showed that the ENDURE could be manufactured more cost effectively than the same as current metal on metal implants, the acetabulum cup would be injection moulded instead of cast / machined and the femoral component would be produced for a similar cost. Using this information it is intended stimulate market sectors for new low wear ceramic on CFR-PEEK implant that will prove a viable alternative to the current technologies.

During the course of the project the process route for the production of the ENDURE components was evaluated and estimations of the cost for the manufacture of the components was determined From this evaluation it was decided to make some minor changes to the design of the acetabulum cup in order to facilitate the manufacture of the components. Both Femoral and acetabulum components were manufacture together with the instrumentation required for the implantation of the components were produced and have been demonstrated at exhibitions and seminars both within the UK and Europe. Evaluation of reproducibility was considered and it was determined that due to the manufacturing route this was a major advantage over current manufacturing routes. It is also intended to use the web site generated during the project to facilitate in the technical transfer of information, however it should be noted that all of the partners have a comprehensive understanding of the technology as a result of attendance at the technical and managerial meetings.

Cost Analysis Discussion

Design studies for the femoral and acetabulum together with the production route chosen for the manufacture of the components indicates that the manufacturing cost would be lower than those for the manufacture and sterilisation of current hip prosthesis. Following investigation it was determined that the average cost of current hip prosthesis components range from is approximately 600 Euros to 2125 Euros whereas we estimate that the new endurance implant will retail for approximately 1600 Euros which as can be seen is significantly less than the upper end of the current implant market. The reason for this is that we feel the production cost for the manufacture of the femoral component will be higher than the current cost for the metal on metal resurfacing hip component. This would be due to the need to form the ceramic head by hot isostatic pressing followed be the machining and polishing techniques require. By 2021 we would look to have increased our presence within the global prosthesis market sector by taking a 7.5% share of this market giving us an estimated 593 million Euros turnover with a predicted 90 million Euros profit.

With the current falling in popularity of the metal on metal hip prostheses we envisage the demand for the ENDURE system will be fuelled by the need for an alternative system. We have already been contact by several patient groups and surgeons who have indicated that they would like more information on the new system. We feel that this increased awareness and demand for an alternative to that of the metal on metal will inevitably result in the increase of our market share for this product. It is also intended to look at transferring the technology developed in to other areas such as knee operations and potentially shoulder joints.

Process production parameters.

During the course of this project the route for manufacture of the ceramic in CFR-PEEK resurfacing hip prosthesis has been reviewed at regular intervals to make sure that the components could be manufactured cost effectively. As a result of this process the design of the final components was modified. In the case of the femoral head it was designed to allow for the use of the existing instrumentation currently used for the implantation of the femoral head. The acetabulum cup also underwent a series of modifications in order to facilitate the production process and materials to be used. These modifications include the development of a location system for the impaction cap that prevents the damage to the cup during implantation. The result of the modification has resulted in the tooling costs being greatly reduced and that the complexity of the tooling has been made as simple as possible, allowing for reproducibility of cost effective and geometrically accurate components.

Market Stimulation of the ENDURE prosthesis

Prototype ENDURE systems have been manufactured and presented at exhibitions and seminars in both the UK and Europe. These samples were manufactured to promoted market interest in the new technology. Samples of the ENDURE prosthesis were supplied to a surgeon for cadaver trials and the information gained from these trials was used to refine the instrumentation. The feedback was also used to critique the operating procedure and from this an operation method was generated for training purposes.

Using the feedback from the cadaver trials it was possible to edit a film of the operation which has subsequently been used to show potential new surgeons how the operation was performed and the results, including the accuracy of the final implanted prosthesis. Using both the film as well as still photos and the prototype instrumentation and implant it is intended to demonstrate the technology at several predefined exhibitions and conferences such as the MedTech Stuttgart, Orthotech Zurich and the international conference for orthopaedics.

Technology transfer and case study demonstration

To facilitate the transfer on knowledge during the course of the project a web site was setup and updated on the regular basis, this gave the partners the opportunity to review the technology and add comments and articles of interest. It is intended to make sections of this web site available to both surgeons and the general public once the patent claims have been finalized. Aurora in conjunction with Adler Ortho and DePuy will also hold training days with both surgeons and theater staff to ensure that the technology developed is transferred in a manner that will ensure the success of the produce once in the market place.

The result of the project have been published on the Fraunhofer web site, as a result of this publicity the Fraunhofer and rest of the partners have been inundated with request for more information. At present the consortium member has been receiving approximately 25 emails from both surgeons and the general public wishing to learn when the technology will be made available and if they can be treated with the new implant during the clinical trial stage of the development. This significant interest in the technology developed has spurred the consortium on to the next phase of development and they are currently look at the clinical trials that will be needed to gain the relevant regulatory approvals.

Dissemination Activities During Period

Despite the early success of the ENDURE project to date, the project remains at an early stage, particularly with regard to exploitation and dissemination of the project results and developed technology. However, the project Consortium and particularly our Exploitation Manager, Mike Tuke, have extended considerable efforts to lay the foundations for the exploitation of the project, with several early successes achieved to date. To facilitate the dissemination of the project results Mike made extensive plans for dissemination and exploitation by the creation of interest within the surgical groups and with surgeons across the orthopaedic sector. In addition, Dr Andy Taylor has been instrumental in the creation of a website that can be viewed by public where all details of the ENDURE public dissemination activities can be found (see http://ENDURE-fp7.com/ online).

To date the project results have been featured in several orthopaedic magazines such as the European Medical Device technology, American orthopaedic and we have even been contact for information from the reader's digest. As well as these publications we have put project information on the Fraunhofer website which again has stimulated a great deal of interest from both surgeons and general public alike. The technology developed during the course of the project has also been presented and several conferences and exhibition, these include the DesignMed Europe conference, Orthotech conference and exhibition and preliminary results were presented at the MedTech conference Stuttgart 2011. It is also intended to present the full project results at these conferences during 2012.

The following table highlights a number of potential dissemination activities that the Consortium intend to carry out (Note that while we have identified these events and technical papers they will not happen until after the project has ended):

Articles

Title Presentation Papers / Journal

Hip implant for long term use Orthotech conference in Zurich 2012

Abstracts 20/09/2012, 2 pages

New breakthrough in resurfacing hip implants Readers digest

UK 2012

Abstracts 2012

Surgical Impaction Loads in Ceramic Hip Resurfacing Engineers and Surgeons: Joined at the Hip 3

IMechE, London, 01/11/2012

Abstracts 31/3/2012, 750 words

An alternative to metal on metal resurfacing American orthopaedic magazine 2012

USA 2012

Abstract 2012

Great debate conference new developments in resurfacing hip implantation. Great Debate conference

London 29-30/06/2012

Impact loads and stress in hip resurfacing International Society for Technology Arthroplasty.

September 2011 Bruges, Belgium

Assessing the Influence of Acetabular cup Material on Pelvic Surface Strains After Hip Replacement using Digital Image Correlation. Society for Technology Arthroplasty, September 2011, Bruges, Belgium.

The influence of acetabular cup material on pelvis cortex surface strains, measured using digital image correlation. Journal of Biomechanics 2012, 23; 45 (4):719-723.

Surgical Impaction of Ceramic Femoral Resurfacing Heads. 35th Annual Meeting of the American Society of Biomechanics (ASB) 2011, Long Beach CA, USA.

Bone Remodelling around the Implanted Hip: Does Material Matter? Tribology of PEEK Workshop, at the 18th European Orthopaedics Research Society meeting - EORS 2010, Davos, Switzerland

Multi-pelvis Characterisation of Articular Cartilage Geometry - Comparison with an Analogue Model. International Society for Technology Arthroplasty, September 2011, Bruges, Belgium.

Multi-pelvis Characterisation of Articular Cartilage Geometry - Comparison with an Analogue Model. Engineering Doctorate conference University of Southampton, December 2011, Southampton.

Multi-pelvis Characterisation of Articular Cartilage Geometry. Submitted to Medical Engineering and Physics.

Engineering Doctorate Thesis - Development of a Novel Hip Prosthesis. Submission due Oct 2013

Simulation in implant development Medtec Europe, innovation forum, march 14th 2012, Stuttgart

In addition to planning project dissemination, the Consortium has already consulted with a patent attorney regarding the potential for protection of the project IPR. Having reviewed the IPR generated during the course of the project we have concluded that the most appropriate form of protection and indeed most robust will primarily be through patenting the completed device which we anticipate to result from the project. A second paten will be taken out on the new design for the impaction cap and more specifically the location mechanism. The Consortium will however remain vigilant of the need to protect the project developments and will continue to take appropriate advice from both our patent attorney and the IPR help desk where appropriate.

List of Websites:

http:// www.endure-fp7.com