E1™ Antioxidant Infused Technology: For Knee and Hip Applications

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Introduction

Since the late 1990s, the orthopedic industry has been developing highly crosslinked polyethylene (HXLPE) materials to capitalize on the increased wear resistance that results from crosslinks[1] formed during high dose, high energy irradiation (i.e. gamma or e-beam). One limitation of this irradiation process is the formation of reaction sites in the crystalline regions of the polyethylene.[1] These reaction sites, or free radicals, can bond with oxygen molecules and begin an oxidation reaction that may result in oxidative degradation of the polyethylene.[1] Therefore, a majority of the development work has focused on methods for eliminating or stabilizing free radicals to prevent the potentially damaging effects of oxidation. The first attempts at eliminating free radicals utilized remelting or annealing to stabilize them. These methods compromised either the mechanical strength or the oxidative stability of the polyethylene.[2,3]

Due to the limitations of remelted and annealed HXLPE, the industry continues to pursue new crosslinked polyethylene materials that significantly reduce wear rates, maintain mechanical properties and prevent oxidative degradation. E1™ Antioxidant Infused Technology was developed by Biomet utilizing technology invented at Massachusetts General Hospital (MGH). E1™ material exhibits impressive oxidative stability, mechanical properties similar to that of ArCom® polyethylene, the gold standard for polyethylene in the orthopedic industry, and highly reduced wear rates.[4–6]

E1™ material is currently the only antioxidant infused polyethylene and the only bearing technology cleared by the FDA with the following claims:

- **E1™ Antioxidant Infused Technology prevents oxidative degradation of polyethylene.[7]**
- **E1™ Antioxidant Infused Technology maintains mechanical strength after accelerated aging.[7]**
- **E1™ Antioxidant Infused Technology maintains the mechanical strength of conventional UHMWPE under small punch testing.[7]**
- **E1™ Vanguard® tibial bearings had a volumetric wear rate that was 86% less than that of a conventional DCM UHMWPE bearing of the same geometry.[7]**

Current Processing Methods

First-generation crosslinked materials differ in the amount of crosslinking and the method used to counteract the decrease in oxidation resistance caused by residual free radicals remaining after irradiation.

Remelting

Some manufacturers reduce the oxidation potential of polyethylene after crosslinking by heating the material above its melt temperature. This remelting allows the free radicals left in the material to combine, which reduces the free radical concentration below detectable levels. Although this process increases the oxidation resistance of the polyethylene, it detrimentally affects the material properties by reducing the tensile and fatigue strengths of the polyethylene.[2,8–10] This reduction in mechanical properties can be present clinically in the form of cracking and fracture.[11–13]

Annealing

Another method used by manufacturers to reduce the concentration of free radicals involves annealing the polyethylene below the melt temperature after crosslinking (Crossfire® polyethylene from Stryker). By staying below the melt temperature during processing, the polyethylene maintains its material properties. However, not all of the free radicals trapped in the crystalline regions of the material are able to combine and therefore remain in the material. Further, these materials are sterilized with gamma irradiation following the annealing process, which increases the quantity of non-stabilized free radicals.[1] Due to these remaining free radicals, studies have shown that irradiated and annealed materials can oxidize *in vivo*.[3,13,14] Recently, this method of annealing was adapted and applied in a sequential process without terminal gamma sterilization to create X3® polyethylene from Stryker Orthopaedics. Currier *et al.* noted "X3 retrievals appear to follow a similar oxidation trend after short *in vivo* time. This oxidation may change the wear resistance of acetabular liners and could lead to fatigue…"[15]

Antioxidant Infused Technology

The Technology

E1™ Antioxidant Infused material, developed by Biomet Orthopedics utilizing technology invented at MGH, is processed below the melt temperature to maintain the strength of the crosslinked polyethylene and infused with vitamin E to stabilize free radicals and prevent oxidative degradation of the polyethylene.[4] Infusing vitamin E into irradiated polyethylene is a novel approach to reducing the oxidation potential of the material.

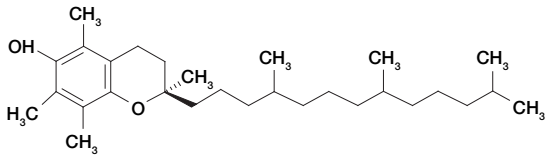

Fig. 1
Vitamin E Molecule

As shown in Figure 1, the vitamin E molecule is made up of a ring structure and a carbon chain. The carbon chain makes the vitamin E molecule hydrophobic, which allows it to be readily diffused into the polyethylene. When a molecule of vitamin E encounters a free radical in the polyethylene, it donates a hydrogen atom from the –OH group on the ring structure. This, in effect, transfers the free radical from the polyethylene chain to the vitamin E molecule.[16] Unlike remelted material, E1™ material still has detectable levels of free radicals, but the key to this technology is the location of those free radicals. After the infusion process, the free radicals detected in the polyethylene are associated with the ring structures on the vitamin E molecule, not the polyethylene molecule. Therefore, if oxygen is introduced into the system, the oxygen molecules would only react with the vitamin E molecules, leaving the polyethylene molecules untouched. In addition, the free radicals associated with the vitamin E molecules are part of the electron field of the ring structures, making it more difficult for oxygen to react with the free radicals.

The Process

The E1™ material process capitalizes on Biomet's advancements in polyethylene by utilizing ArCom® barstock as the starting material (both 1020 and 1050 resin used). ArCom® barstock is manufactured in-house in a hot-isostatic compression molding process that produces high-quality, consistent barstock.

To begin the process, ArCom® barstock is machined, packaged and gamma irradiated to a dose of 100kGy (10Mrad). The irradiation process crosslinks the polymer chains, which increases the wear resistance of the polyethylene. After irradiation, the parts are infused with vitamin E. By processing below the melt temperature of polyethylene, the mechanical properties are maintained. Vitamin E is infused into the polyethylene for the sole purpose of stabilizing free radicals, and does not contribute to the reduction in wear. After the parts are infused with vitamin E, they are machined into the final geometry, cleaned, packaged and gamma sterilized.

Biomet and MGH have collaborated to create this revolutionary crosslinked polyethylene that exhibits impressive oxidative stability while maintaining mechanical properties similar to that of ArCom® polyethylene.

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Knee Applications

Introduction

This section will present mechanical and device testing results for E1™ Antioxidant Infused Tibial Bearings.

Oxidative Stability

Environmental Stress Cracking Study[1,2]

Cyclic loading, combined with the *in vivo* environment, may potentially induce the formation of cracks in polyethylene. This phenomenon is referred to as environmental stress cracking (ESC). ESC in polyethylene is related to the amount of non-stabilized free radicals in the material, the number of free radicals induced during loading and the ability for those free radicals to react with oxygen.

Materials and Methods

Massachusetts General Hospital

E1™ Antioxidant Infused Technology for knee applications was tested to determine its resistance to ESC. The ESC resistance was evaluated in air by cyclically loading test samples on a mechanical test frame in an environmental chamber kept at 80°C for five weeks or until the samples failed. Failure of a sample was defined as the visible appearance of cracks in the surface of the triangular neck region or a complete shear fracture of the neck (Figure 1). Four E1™ specimens were loaded, and an additional three specimens were kept in the chamber at 80°C during the test without applying any load as control samples.

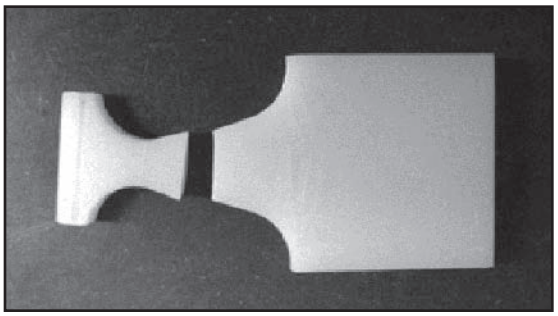

Fig. 1
Example of a Shear Failure

Upon specimen failure or the conclusion of five weeks of cyclic loading (whichever came first), the samples were analyzed by Fourier Transform Infrared Spectroscopy (FTIR, Bio-Rad FTS2000, Natick, MA) to quantify the oxidation within the triangular neck region. Oxidation levels were expressed as an oxidation index. The oxidation profiles of the E1™ samples are included in Figure 2. Also included in Figure 2 are oxidation profile results for a sequentially crosslinked and annealed material presented in the literature that underwent the same testing.*

Results

- Half of the sequentially crosslinked and annealed samples sheared in two, as shown in Figure 1.[2]
- E1™ samples showed no evidence of environmental stress cracking.
- Oxidation indices for the sequentially crosslinked and annealed material were higher in the loaded specimens than in the unloaded controls (Figure 2).
- E1™ specimens showed little to no detectable oxidation in the loaded or unloaded samples (Figure 2).
- **FDA Cleared Claim: E1™ Antioxidant Infused Technology prevents oxidative degradation of the polyethylene.**[3]

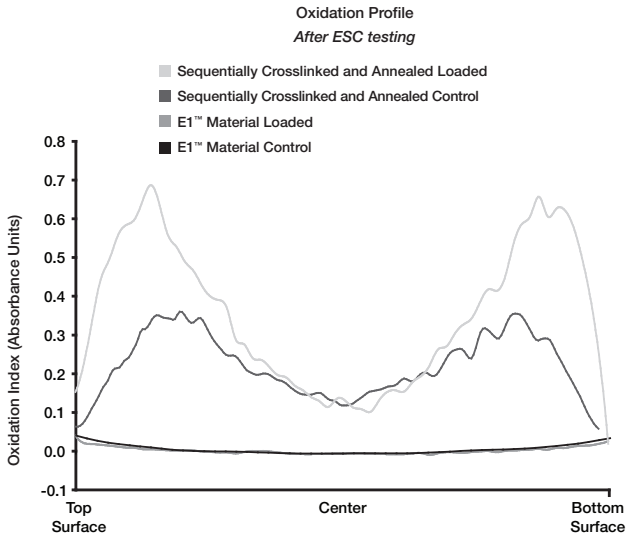

Fig. 2
Average Oxidation Profiles of E1™ and Sequentially Crosslinked and Annealed (SXL) Samples

*GUR1050 UHMWPE that was 33kGy gamma irradiated and annealed at 130 degrees Celsius for 5 hours and slow cooled and repeated twice more.

Small Punch Testing

Materials and Methods

Exponent

Small punch testing, combined with accelerated aging was used to show oxidative stability under severe aging conditions. Testing was completed per ASTM F2183-02 on unaged, 2-week bomb aged, and 4-week pressure vessel aged gamma sterilized DCM UHMWPE and E1™ specimens.[4] Pressure vessel aging was completed at 70°C in 5 atm of oxygen. The ultimate load results for samples taken from the surface of the specimens are shown in Figure 3. The surface results for ultimate displacement, peak load and energy to failure are shown in Table 1.

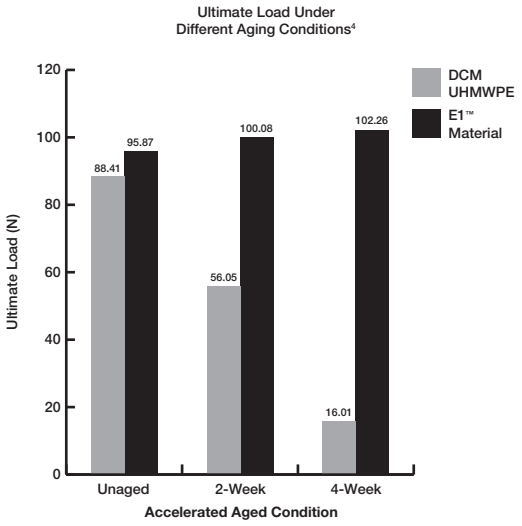

Fig. 3
Small Punch Ultimate Load for E1™ and Gamma Sterilized DCM Materials Under Normal and Severe Accelerated Aging

Results

- The peak loads and energies to failure were similar for all four material groups.
- Ultimate load of the E1™ specimens was higher than that of the gamma sterilized DCM material for all aging conditions.
- There was no decrease in the ultimate load, peak load, ultimate displacement or energy to failure of the E1™ material after 2- and 4-week accelerated aging.
- **FDA Cleared Claim: E1™ Antioxidant Infused Technology maintains the mechanical strength of conventional UHMWPE under small punch testing.[3]**

Wear Testing

Large Contact Area: Cruciate Retaining (CR)

Materials and Methods

Biomet Biomaterials Laboratory

Wear testing was performed per Biomet test procedure 49 in accordance with ISO 14243 (where applicable) on an AMTI 6-station Knee Simulator under force control conditions. The three test and two load soak components were soaked in clean water for 14 days prior to testing. Gravimetric measurements were taken every 500,000 cycles to a total of 5 million cycles. The test frequency was 1 Hz. Bovine calf serum diluted to a protein concentration of 20 g/L was used as lubricant. The wear rates of the largest E1™ bearing profile (10x87/91) were compared to that of gamma sterilized DCM Vanguard® tibial bearings of the same geometry. The volumetric wear rates are presented in Figure 4.[5]

Results

- **FDA Cleared Claim: The Biomet E1™ Vanguard® Tibial Bearings had a volumetric wear rate that was 86% less than that of a conventional DCM UHMWPE.[3]**

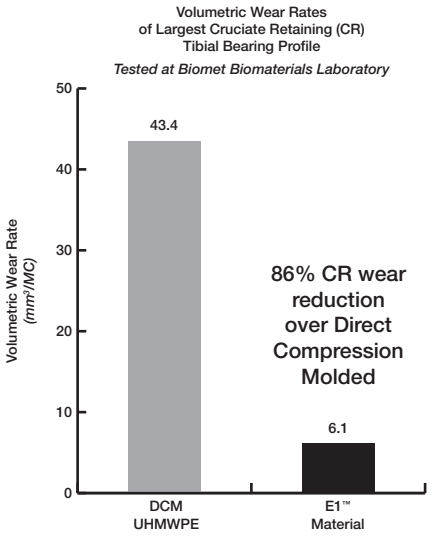

Fig. 4
Volumetric Wear Rates for Large Contact Area E1™ and DCM UHMWPE CR Tibial Bearings

Table 1: Small Punch Results from Surface of Specimens. Standard Deviations are in Parentheses.						
Material Properties	Gamma Sterilized DCM, Unaged	Gamma Sterilized DCM, Aged (2 wk)	Gamma Sterilized DCM, Aged (4 wk)	E1™ Material, Unaged	E1™ Material, Aged (2 wk)	E1™ Material, Aged (4 wk)
	Average	Average	Average	Average	Average	Average
Ultimate Displacement (mm)	4.45 (.32)	3.99 (0.16)	2.69 (0.43)	3.92 (0.39)	4.13 (0.51)	4.22 (0.36)
Peak Load (N)	74.71 (3.96)	71.28 (3.06)	71.96 (3.47)	70.27 (0.94)	71.10 (1.21)	71.47 (1.91)
Mean Energy to Failure (mJ)	268.4 (24.3)	198.1 (13.4)	118.4 (12.2)	236.7 (38.7)	261.9 (54.3)	274.7 (40.3)

Large Contact Area: Posterior Stabilizing (PS)

Materials and Methods

University of Nebraska

Wear testing was performed on PS Vanguard® E1™ and gamma sterilized DCM tibial bearings with the largest profile (10x87/91). Testing was completed at the University of Nebraska per ISO standard 14243 under force control. The volumetric wear rates are reported in Figure 5.

Results

- **The E1™ Antioxidant Infused PS tibial bearings had a volumetric wear rate that was 87% less than that of the conventional DCM UHMWPE.[6]**

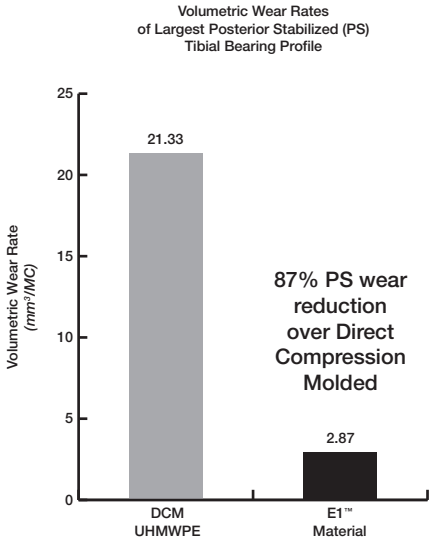

Fig. 5
Volumetric Wear Rates for Large Contact Area E1™ and DCM UHMWPE PS Tibial Bearings

CR Wear Debris Analysis

Materials and Methods

Loma Linda University

Polyethylene particles generated *in vivo* can frustrate the immune system and increase the risk of bone resorption and osteolysis. When highly crosslinked polyethylene was first introduced to the orthopedics market, there was concern that the number of particles stayed the same, but the particles were much smaller. Wear particle analysis was conducted using serum samples collected from the large contact area CR wear study to compare the particle morphologies of the E1™ material to that of DCM UHMWPE. The particles were isolated using a hydrochloric acid digestion method[7] and analyzed for the equivalent circular diameter, aspect ratio and circular shape factor (Table 2). Based on the wear rates and the number of debris particles, the investigators were able to estimate the number of particles generated per million cycles of testing (Figure 6).

Table 2: Average Particle Analysis Results for E1™ and DCM Materials		
Morphological Parameter	DCM UHMWPE	E1™ Material
Equivalent Circular Diameter (µm)	0.791 ± 0.535	1.076 ± 0.818
Aspect Ratio	1.622 ± 0.593	1.749 ± 0.721
Circular Shape Factor	0.775 ± 0.112	0.733 ± 0.113

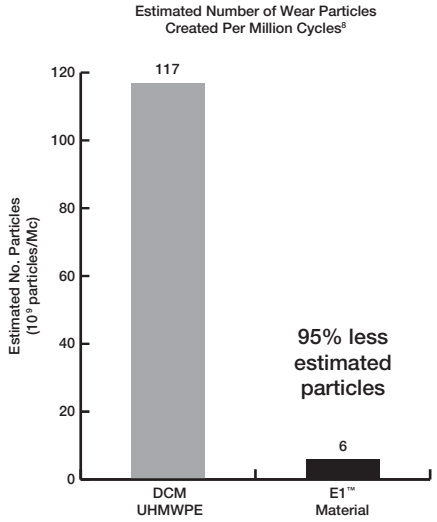

Fig. 6
Estimated Number of Wear Particles Generated During Simulator Testing

Results

- Morphology of the E1™ particles is similar to that of the DCM UHMWPE particles.
- **Based on the results of the particle analysis, it is estimated that the E1™ material produced 95% less particles than the DCM control material.[8]**

Mechanical Properties

Maintaining the tensile and fatigue properties after crosslinking polyethylene is vital to the integrity of locking mechanisms and posterior stabilizing posts when they are subjected to normal and adverse loading conditions *in vivo*. Biomet has carried out extensive mechanical testing to prove that the E1™ bearings have similar mechanical properties to that of DCM ArCom® polyethylene. The testing included post fatigue, tensile strength, fatigue crack propagation resistance and impact strength.

Both unaged and accelerated aged specimens were tested to provide further evidence of the oxidative stability of the E1™ material. Accelerated aging was completed in a pressure vessel at 70°C and 5 atm of oxygen for two weeks in accordance with ASTM F2003.

Post Fatigue[9]

Materials and Methods

Biomet Biomaterials Laboratory

The purpose of this study was to test the integrity of the post in posterior stabilizing designs under fatigue loading. For this study, the component combination of a 10x71/75 PS E1™ Antioxidant Infused tibial bearing and an 80 mm PS femoral component provided the worst case scenario for testing the post fatigue resistance of the E1™ bearing. Five samples of unaged E1,™ aged E1™ and unaged conventional DCM material were tested.

The test setup is shown in Figure 7. All samples were tested using a cyclic load curve with a minimum load of 130 lbs and a maximum load of 1300 lbs. The test ran for 3 million cycles at 20 Hz. This loading is identical to that used for previous testing.[10] Failure was defined as a sudden increase in displacement, or a total post displacement perpendicular to the post of 0.1".

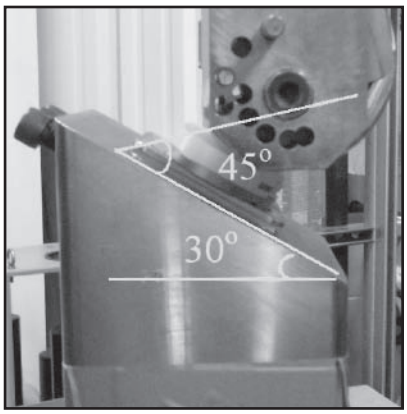

Fig. 7
Post Fatigue Test Setup

Results:

- Upon visual inspection of the impingement region (Figures 8–10), there were no noticeable differences between the control group and the E1™ specimens. There was also no evidence of cracking or other gross damage.
- There were no discernable differences in the impingement region between the aged and unaged E1™ specimens.
- Accelerated aging had no effect on the post fatigue resistance of the E1™ material.

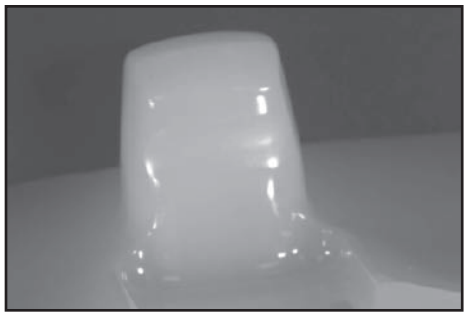

Fig. 8
Unaged Conventional DCM UHMWPE

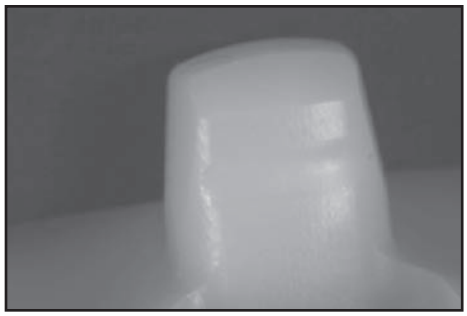

Fig. 9
Unaged E1™ Material

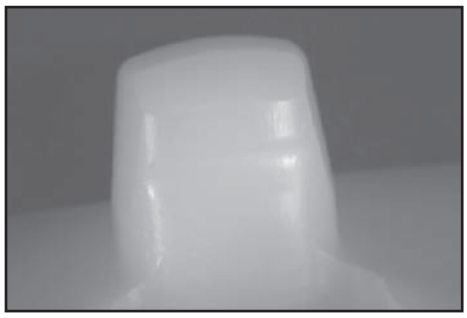

Fig. 10
Aged E1™ Material

Tensile Properties

Materials and Methods

Bodycote Laboratories

Tensile testing was completed per ASTM standard D638.[11] Type V dog bone specimens were processed using methods identical to those used to manufacture E1™ tibial bearings. Half of the specimens underwent accelerated aging prior to testing. Five specimens were tested in each group. The ultimate tensile and yield strengths are shown in Figure 11. The tensile and yield strengths for 100kGy crosslinked and remelted UHMWPE (tested per the same ASTM standard)[12] are also included in Figure 11 for reference.

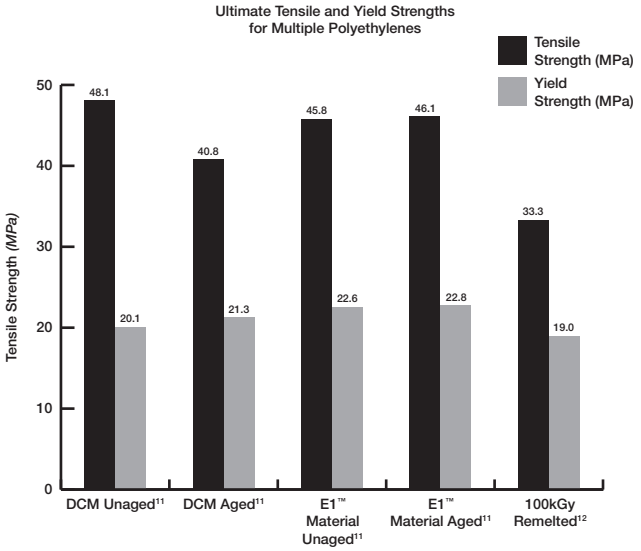

Fig. 11
Ultimate Tensile and Yield Strengths of Multiple Polyethylenes

Results

- E1™ material has a higher ultimate tensile and yield strength than irradiated and remelted UHMWPE.
- **FDA Cleared Claim: E1™ Antioxidant Infused Technology maintains mechanical strength after accelerated aging.[3]**

Crack Propagation Resistance

Materials and Methods

Exponent

Fatigue crack propagation testing is used to evaluate the fatigue performance of a material once a crack has initiated. The fatigue crack propagation testing was carried out per ASTM standard E647. Circular C(T) specimens were processed using methods identical to those used for E1™ tibial bearings. Half of the specimens underwent accelerated aging prior to testing. Four specimens were tested for each of the two E1™ material groups. Values were recorded for ΔK inception, or the minimum stress intensity factor at which a crack will propagate (Table 3).

Results

- ΔK inception for the E1™ material group was slightly lower than that of the DCM conventional material due to the increased crosslinking in the E1™ material.
- It requires less load to propagate a crack through the remelted material than that of the E1™ material.

Table 3: ΔK Inception of Different Polyethylenes	
Material Description	ΔK Inception (MPa·√m)
DCM Conventional UHMWPE[4]	1.3
E1™ Technology[4]	1.2
100kGy Irradiated and Remelted[13]	0.9
Irradiated and Annealed[13]	1.1

Impact Strength

Materials and Methods

Biomet Biomaterials Laboratory

Impact strength was measured using the technique presented in ASTM standard F648. Half of the E1™ specimens were accelerated aged at 5 atm of oxygen and 70°C for two weeks. The impact strength results are included in Figure 12.[14] The average impact strength of 100kGy irradiated and remelted polyethylene is also included.[15]

Results

- **Impact strength of the E1™ material is higher than that of the irradiated and remelted material.**

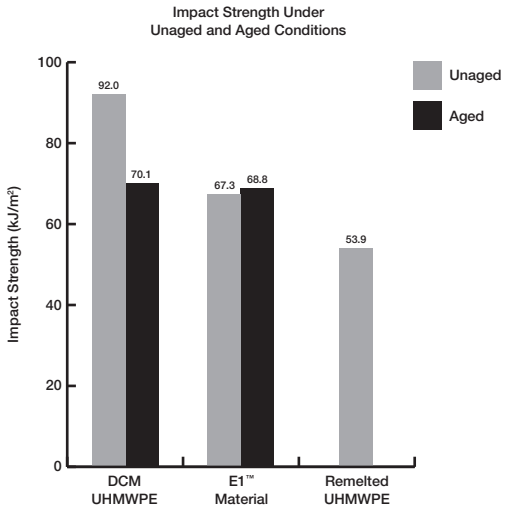

Fig. 12
IZOD Impact Strength of Three Polyethylenes

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Hip Applications

Introduction

This section will present mechanical and device testing results of E1™ Antioxidant Infused acetabular liners.

Wear Performance

High Contact Stress

Materials and Methods

Biomet Biomaterials Laboratory

To test the worst-case scenario for contact stress, the smallest, thinnest E1™ liners were tested. Size 22 liners with a 28 mm inside diameter and a nominal wall thickness of 4.8 mm were tested on an orbital hip simulator. The simulator utilized a standard walking curve with a peak load of 2400N for 5 million cycles and a serum protein concentration of 20 g/L. The parts were tested under clean conditions against CoCr modular heads, and gravimetric measurements were taken every 500,000 cycles. Results were gathered for the average volumetric wear rates of E1™ liners run on an orbital simulator and for ArCom® and ArComXL® liners run on an equivalent orbital simulator in a previous study.[1]

Results

- **The average volumetric wear rate of 28 mm E1™ liners was more than 99% lower than those of ArCom® and ArComXL® liners (Figure 1).[1]**

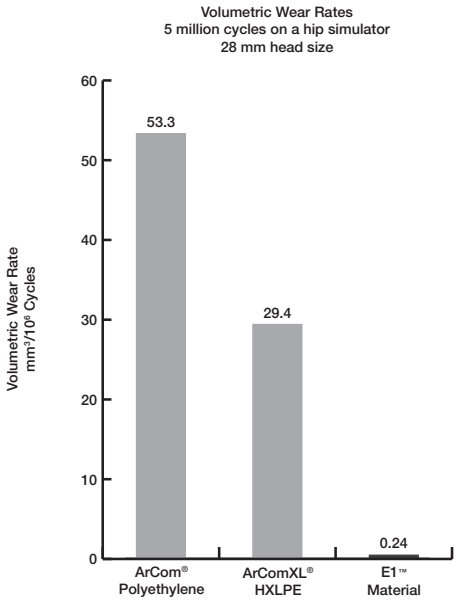

Fig. 1
Volumetric Wear Rates for 28 mm Acetabular Liners

High Contact Area

Large diameter femoral heads have a larger contact area in polyethylene liners than small diameter heads. As a result, they have the potential to produce more wear debris and have higher wear rates than smaller diameter components when coupled with polyethylene liners.

Materials and Methods

Biomet Biomaterials Laboratory

The volumetric wear rate of 25x38 mm E1™ liners was compared to the volumetric wear rate of 25x38 mm ArComXL® liners coupled with both CoCr and ceramic modular heads. The components were tested on an AMTI hip simulator with anatomical motion for 5 million cycles. The study was carried out per ISO 14242-1. Load soaks were used to account for fluid uptake during testing. Bovine calf serum with a protein concentration of 20 g/L was used as the lubricant. Gravimetric measurements were taken every 500,000 cycles.

Results

- **The average volumetric wear rate for 38 mm E1™ liners coupled with metal heads was 89% less than that of the 38 mm ArComXL® liners (Figure 2).[1]**
- **38 mm E1™ liners coupled with ceramic heads had a similar wear rate to that of metal-on-metal run-in wear.[1]**

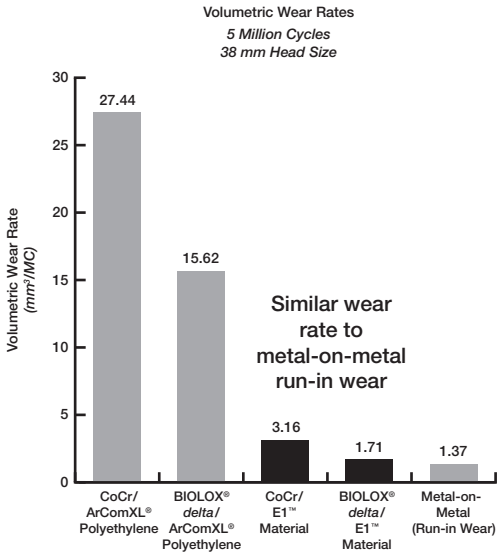

Fig. 2
Volumetric Wear Rates for Large Diameter E1™ and ArCom® XL Liners

Wear Particle Analysis

Materials and Methods

Loma Linda University Medical Center

Polyethylene particles generated *in vivo* can frustrate the immune system and increase the risk of bone resorption and osteolysis. Wear particle analysis was conducted using serum samples collected from a 40 mm wear study under clean conditions (MT4071[1]) to compare the particle morphologies of the E1™ material to that of ArCom® polyethylene. The E1™ particles were processed using a hydrochloric acid digestion method,[2] then analyzed for the equivalent circular diameter, aspect ratio and circular shape factor (Table 1).

Table 1: Particle Analysis Results for E1™ and ArCom® Materials

Parameters	Statistic	ArCom®[1] N=363 Particles	E1™[1] N=867 Particles
Equivalent Circular Diameter (microns)	Mean +/- St. Deviation	0.409 ± 0.591	0.340 ± 0.214
	Median	0.263	0.274
	Minimum–Maximum	0.053 – 3.547	0.100 – 2.28
Aspect Ratio	Mean +/- St. Deviation	1.547 ± 0.532	1.64 ± 0.63
	Median	1.42	1.50
	Minimum–Maximum	1.00 – 7.31	0.100 – 9.58
Circular Shape Factor	Mean +/- St. Deviation	0.860 ± 0.128	0.847 ± 0.105
	Median	0.880	0.872
	Minimum–Maximum	0.170 – 1.220	0.180 – 0.997

Results

- Wear particle morphology of E1™ material is similar to that of the ArCom® material and within parameters for wear particles seen in polyethylene currently in clinical use.[3,4]
- With the same morphology and a lower wear rate, wear of E1™ liners generated less particles during simulator testing than ArCom® liners.

Oxidative Stability

Environmental Stress Cracking Study[5]

For polyethylene acetabular liners, cyclic loading, combined with the *in vivo* environment, may potentially induce cracks in polyethylene. This phenomenon is referred to as environmental stress cracking (ESC). ESC in polyethylene is related to the amount of non-stabilized free radicals in the material, the number of free radicals induced during loading and the ability for those free radicals to react with oxygen.

Materials and Methods

Massachusetts General Hospital

E1™ material, conventional polyethylene (gamma-inert sterilized and removed from packaging) and sequentially crosslinked and annealed samples* were tested to determine their resistance to ESC. The ESC resistance was evaluated by cyclically loading test samples on a mechanical test frame in an environmental chamber kept at 80°C for five weeks or until the samples failed. Failure of a sample was defined as the visible appearance of cracks in the surface of the triangular neck region or a complete shear fracture of the neck (Figure 3). Four specimens from each group were tested, and an additional three specimens were kept in the chamber at 80°C during the test without applying any load so that the effect of loading could be determined.

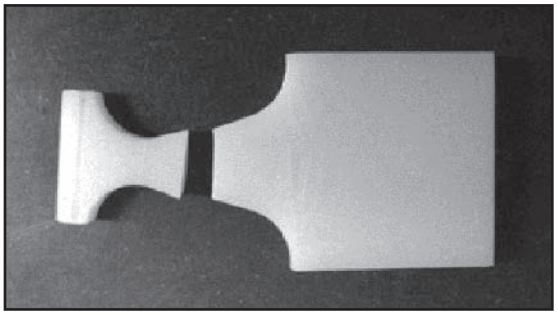

Fig. 3
Sheared Sequentially Annealed Specimen

*GUR1050 UHMWPE that was 33kGy gamma irradiated and annealed at 130 degrees Celsius for 5 hours, slow cooled and repeated twice more.

Table 2: Total Number of Cycles Completed by the Individual Samples. If the Samples Failed Less Than Five Weeks into the Test, the Method of Failure is Noted		
Sample Number	Failed Prior to 5 Weeks?	Cycles Completed
Conventional UHMWPE (gamma inert, removed from packaging)		
A1	Yes *(ESC observed)*	1,410,000 cycles
A2	Yes *(ESC observed)*	1,410,000 cycles
A3	Yes *(ESC observed)*	1,080,000 cycles
A4	Yes *(ESC observed)*	907,200 cycles
Sequentially Crosslinked and Annealed UHMWPE		
X1	No	1,530,000 cycles
X2	No	1,530,000 cycles
X3	Yes *(Sheared in half)*	1,500,000 cycles
X4	Yes *(Sheared in half)*	1,140,600 cycles
E1™ Antioxidant Infused Material		
H1	No	1,530,000 cycles
H2	No	1,530,000 cycles
H3	No	1,530,000 cycles
H4	No	1,530,000 cycles

Upon specimen failure or the conclusion of five weeks of cyclic loading (whichever came first), the samples were analyzed by Fourier Transform Infrared Spectroscopy (FTIR, Bio-Rad FTS2000, Natick, MA) to quantify the oxidation within the triangular neck region. Oxidation levels were expressed as an oxidation index (Figures 4–6).

Results

- Half of the sequentially crosslinked and annealed samples sheared in half (Table 2).
- E1™ samples showed no evidence of environmental stress cracking (Table 2).
- E1™ specimens showed no detectable oxidation in the loaded or unloaded samples (Figure 4).
- Oxidation indices were higher for the conventional and sequentially crosslinked and annealed polyethylene test samples than those for the unloaded controls (Figures 5 and 6).
- **FDA Cleared Claim: E1™ Antioxidant Infused Technology protects polyethylene from oxidation and cracking during environmental stress crack testing.[6]**

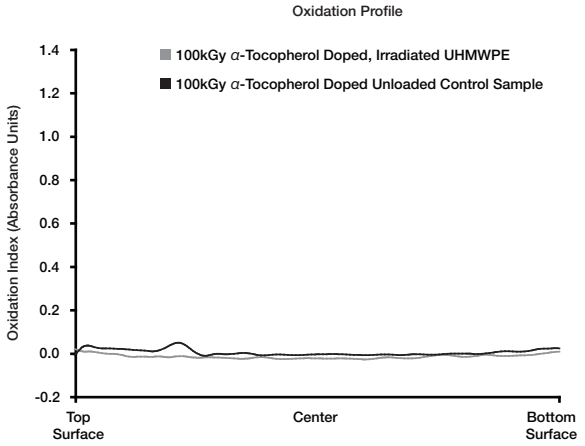

Fig. 4
Oxidation Profiles of E1™ Specimens

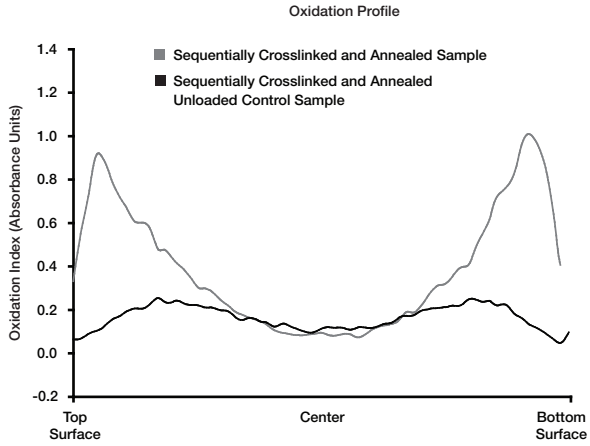

Fig. 5
Oxidation Profile of Sequentially Crosslinked and Annealed Specimen

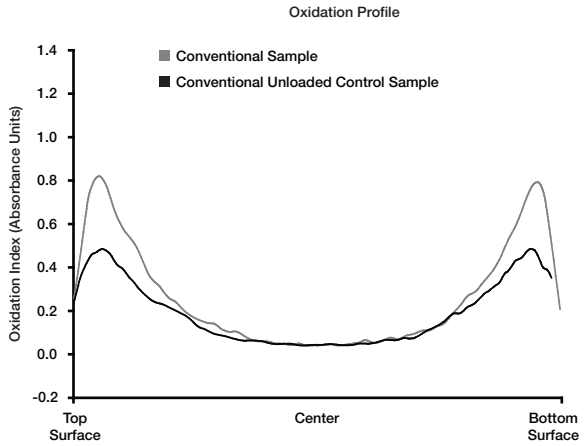

Fig. 6
Oxidation Profile of Conventional Specimen

Small Punch Testing

Materials and Methods

Exponent

Small punch testing, combined with accelerated aging, was used to show oxidative stability under severe aging conditions. Testing was completed per ASTM F2183-02. Six aged and six unaged E1™ material surface specimens were tested for peak load, ultimate load, ultimate displacement and work to failure (Table 3).

Table 3: Small Punch Results for ArCom® and E1™ Materials Average Values of Mechanical Properties[1]

Material Description	Peak Load (N)	Ultimate Load (N)	Ultimate Displace-ment (mm)	Energy to Failure (mJ)
ArCom® Non-aged	72.2±1.8	75.4±5.3	3.96±0.15	223±12
Conven-tional Aged*	75.6±1.1	42.6±16.0	4.16±0.28	211±10
E1™ Non-aged	74.3±2.4	105±5.5	3.4±0.20	209±24
E1™ Aged	78.9±1.5	115±3.2	3.7±0.20	255±19

*Gamma-inert sterilized, removed from packaging.

Results

- The peak loads and energies to failure were similar for all four material groups.
- Ultimate load of the E1™ specimens was significantly higher than that of the ArCom® material, especially under aged conditions.
- Ultimate displacements of the E1™ material were slightly lower than those of the ArCom® material because of the increase in crosslink density.
- Aging of the E1™ specimens had no detrimental effects on the small punch mechanical properties of the material.
- **FDA Cleared Claim: E1™ Antioxidant Infused Technology maintains the mechanical strength of conventional UHMWPE under small punch testing.[6]**

Mechanical Properties

Maintaining the tensile and fatigue properties after crosslinking polyethylene is vital to the integrity of locking mechanisms and extended lip liners when they are subjected to normal and adverse loading conditions *in vivo*.

Biomet has carried out extensive mechanical testing to show that the E1™ liners have similar mechanical properties to ArCom® liners, which have 10 years of successful clinical history.[7] The testing included tensile strength, crack propagation resistance, bending fatigue to test crack initiation and rim impingement fatigue.

With the exception of the two device tests, accelerated aged specimens were tested in addition to the unaged specimens to provide further evidence of the oxidative stability of the E1™ material. The accelerated aging was done in a pressure vessel at 70°C and 5 atm of oxygen for two weeks in accordance with ASTM standard F2003.

Tensile/Yield Strength

Materials and Methods

Bodycote Polymer, Broutman Laboratory

The tensile testing was carried out per ASTM standard D638. Type V dog bone specimens were processed using methods identical to those used for E1™ acetabular liners. Half of the specimens underwent accelerated aging prior to testing. Five specimens were tested in each group to gather average ultimate tensile and yield strengths (Figures 7 and 8).

Results

- Ultimate tensile strength and yield strength of the E1™ material were similar to those of the ArCom® material and higher than those of the remelted materials.
- **FDA Cleared Claim: E1™ Antioxidant Infused Technology maintains mechanical strength after accelerated aging.[6]**

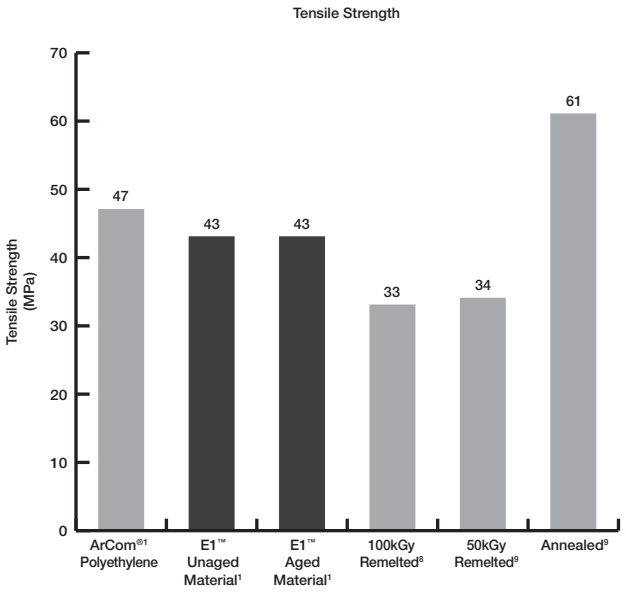

Fig. 7
Ultimate Tensile Strength of Multiple Polyethylenes

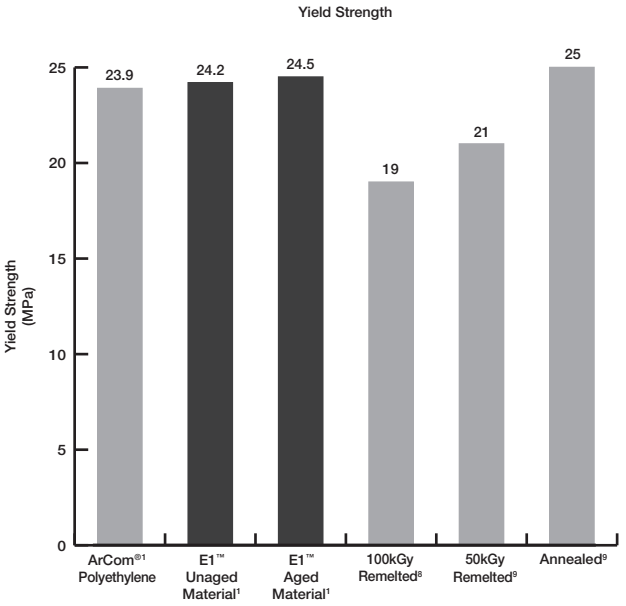

Fig. 8
Yield Strength of Multiple Polyethylenes

Crack Propagation Resistance

Materials and Methods

Case Western Reserve University

Fatigue crack propagation testing is used to evaluate the fatigue performance of a material once a crack has initiated. The fatigue crack propagation testing was carried out per ASTM standard E647. Circular C(T) specimens were processed using methods identical to those used for E1™ acetabular liners. Half of the specimens underwent accelerated aging prior to testing. Four specimens were tested for each of the two E1™ material groups. Values were recorded for ΔK inception, or the minimum stress intensity factor at which a crack will propagate (Table 4).

Results

- ΔK inception for the two E1™ material groups was slightly lower than that of the ArCom® polyethylene control due to the increased crosslinking in the E1™ material.
- **It requires less load to propagate a crack through the remelted material than that of the E1™ material.**

Table 4: ΔK Inception of Different Polyethylenes	
Material	ΔK Inception (MPa·√m)
ArCom® Polyethylene[1]	1.8
ArComXL® Polyethylene[1]	1.4
E1™ Unaged Material[1]	1.1
E1™ Aged Material[1]	1.1
100kGy Remelted[10]	0.9
100kGy Annealed[10]	1.1

Bending Fatigue

Although understanding how a crack propagates through a material is necessary, it is also important to understand the material's level of resistance to crack initiation.

Materials and Methods

Massachusetts General Hospital

The crack initiation behavior of the E1™ material was quantified by cyclically loading the post of the UHMWPE bending specimen (Figure 9). The post had a rectangular cross section and was impinged upon by load applicators due to the upward and downward movement of the actuator. This motion created regions of alternating stress states (compression and tension) that caused cracks to initiate. The number of cycles it took to initiate a crack varied with load.

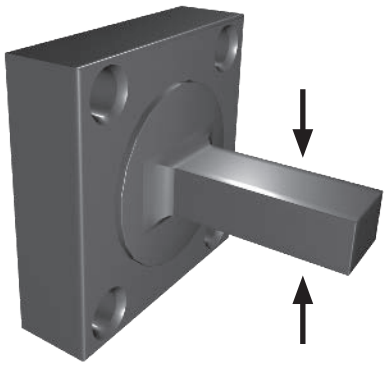

Fig. 9
Bending Fatigue Specimen

This study was conducted on a mechanical test frame in an aqueous environment at 40°C to simulate *in vivo* conditions. The displacement corresponding to the maximum and minimum loads for each load cycle was recorded. Failure initiation was defined as a sudden increase in displacement, and in most cases, the post sheared off and separated from the base within 50–100 cycles of failure initiation. The E1™ and ArCom® specimens tested were compared on an S-N curve (Figure 10).[1]

Results

- Aged and unaged E1™ material groups showed an equivalent resistance to bending fatigue as the clinically proven ArCom® unaged material.

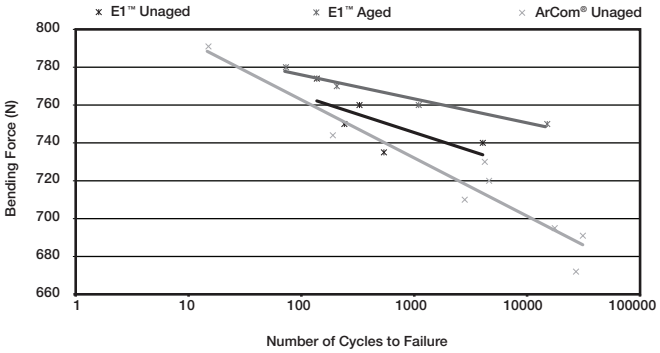

Fig. 10
Bending Fatigue Resistance

Rim Impingement Testing

Rim impingement loading can occur *in vivo* as a result of misalignment or patient movements that require a large range of motion. The worst case for this type of loading is a small, thin hi-wall liner where the point of impact is the top of the wall.

Materials and Methods

Biomet Biomaterials Laboratory

To simulate rim impingement loading conditions, a fatigue test was used, where the trunnion of the stem was in contact with the rim of the acetabular liner when the load was applied (Figure 11). Loading at this point allowed deflection of the polyethylene and produced a higher load at the base of the wall due to the moment arm. The smallest thinnest liners provided less support for the loaded portion of the liner and were theoretically more susceptible to fracture than larger liner designs. The E1™ liners were compared to ArCom® liners of the same size.

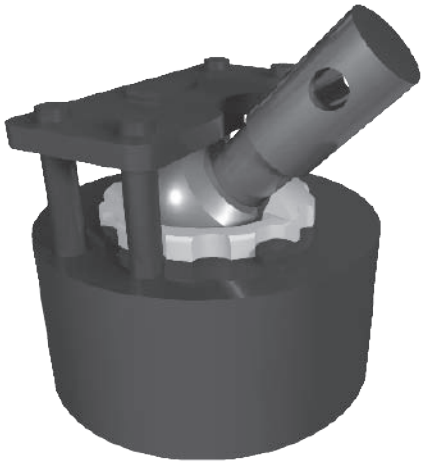

Fig. 11
Experimental Setup for Rim Impingement Loading

This study was run at 5 Hz for 2 million cycles using size 22x28 mm hi-wall acetabular liners. A diagram of the experimental setup is included as Figure 11. The liners were locked in place using the standard RingLoc® locking mechanism. The trunnion was loaded such that the moment at the center of the modular head was 100 in-lbs.[11] To reach this moment, the trunnion was loaded from 10 to 100 lbs. At 500,000 cycle intervals, the test was stopped and liners were photographed and visually inspected for signs of fatigue failure. The area of impingement was outlined using permanent marker. At the end of the 2 million cycles, the liners were removed from the fixture by shrinking them with exposure to liquid nitrogen to bypass the locking mechanism. The backsides of the liners were also visually inspected for signs of damage.

Results

- Impingement region for the 100 kGy E1™ liners was very similar to that for the ArCom® liners (representative pictures included in Figure 12).[1]
- Regions appeared larger at each time point for both materials, which was likely the result of creep.
- Visual liner inspection showed no cracking, pitting or other gross damage to the ID or OD of the E1™ liner or the clinically proven ArCom® polyethylene liners.[1]

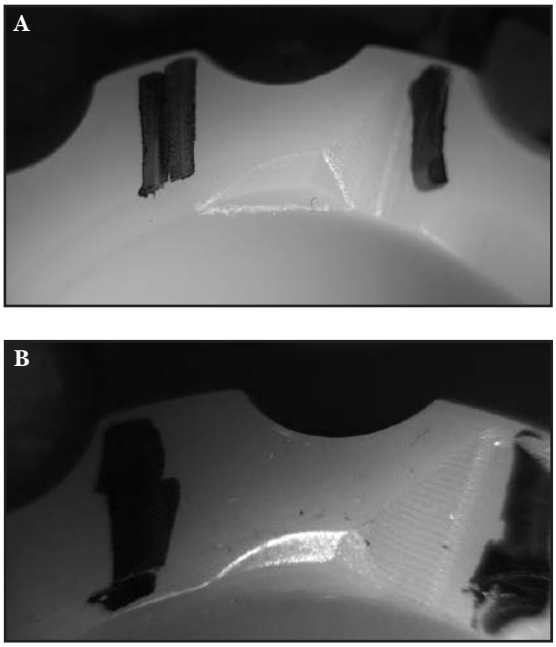

Fig. 12
(A) E1™ Liner at 2 Million Cycles
(B) ArCom® Liner at 2 Million Cycles

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1. Data on file at Biomet. Bench test results not necessarily indicative of clinical performance.
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Elution and Biocompatibility

Elution Testing[1,2]

With any process where one material is infused into another, there is the risk that the infused material may elute out of the parent material over time. Biomet invested a great deal of time and energy into drastically reducing this risk by carefully designing the manufacturing process for E1™ Antioxidant Infused knee and hip bearings.

Materials and Methods

Biomet Biomaterials Laboratory

To quantify the elution from the surface of the E1™ liners and bearings, components were placed in a water bath at 40°C for six months. From the baseline, time points were set at two weeks, two months, four months and six months. Three components from each group were pulled and sacrificed at each time point for FTIR analysis to determine the average surface concentration of vitamin E. The surface layer was defined as the first 20 percent of the normalized thickness of each specimen. The surface vitamin E indices for the acetabular liners and the tibial bearings are shown in Figures 1 and 2 respectively.

Acetabular Liner Results

- The baseline vitamin E indices were higher than those at other time points through the entire surface layer of the polyethylene, suggesting that the baseline liners had vitamin E profiles that were higher through the entire polyethylene thickness and therefore, the difference was not due to elution. If the difference was the result of elution of vitamin E, the indices would converge toward the other groups as the depth increased.
- **There was no detectable vitamin E elution from the surface of the acetabular liners.**

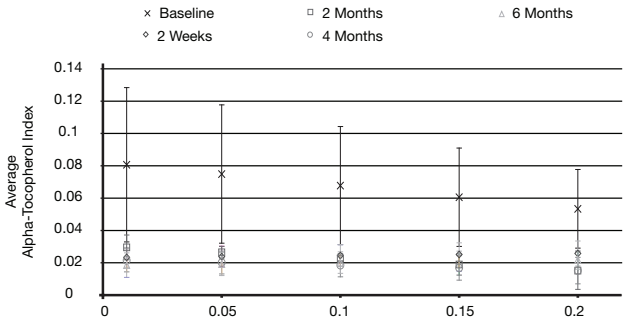

Fig. 1
Surface Vitamin E Indices of Acetabular Liners After Elution Testing

Tibial Bearing Results

- **There was no detectable vitamin E elution from the surface of the tibial bearings.**

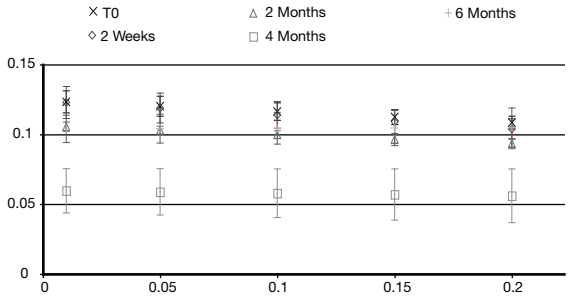

Fig. 2
Surface Vitamin E Indices of Tibial Bearings After Elution Testing

Biocompatibility Testing

In addition to the elution studies, researchers at Massachusetts General Hospital conducted two biocompatibility studies that looked at the tissue response to vitamin E UHMWPE.

Study One[3]

Materials and Methods

Massachusetts General Hospital

In the first study, small plugs of crosslinked and vitamin E infused UHMWPE were implanted in the mid-back region of multiple rabbits. The control material used was a gamma sterilized UHMWPE plug with the same geometry as the test plug. The rabbits were sacrificed at 2 and 12 weeks and the fibrous tissue sacks were harvested and examined by a pathologist.

Results

- Two weeks: the membrane around both control and vitamin E impregnated polyethylene contained numerous macrophages and fibroblasts, which presumably, represented a response to the surgical procedure (Figure 3A).
- Twelve weeks: the encapsulating membrane consisted of a thin layer of fibrous tissue lined by several layers of synoviocyte-like cells (Figure 3B).
- No significant inflammatory infiltrate or foreign body reaction associated with either type of plug.
- No discernible difference in the tissue response to the control polyethylene or the vitamin E impregnated implants at either 2 or 12 weeks after implantation.
- This subcutaneous implant study indicated no deleterious tissue reaction to vitamin E impregnated polyethylene when it was in direct intimate contact with the surrounding tissue, indicating that it will be well tolerated as an implanted material.

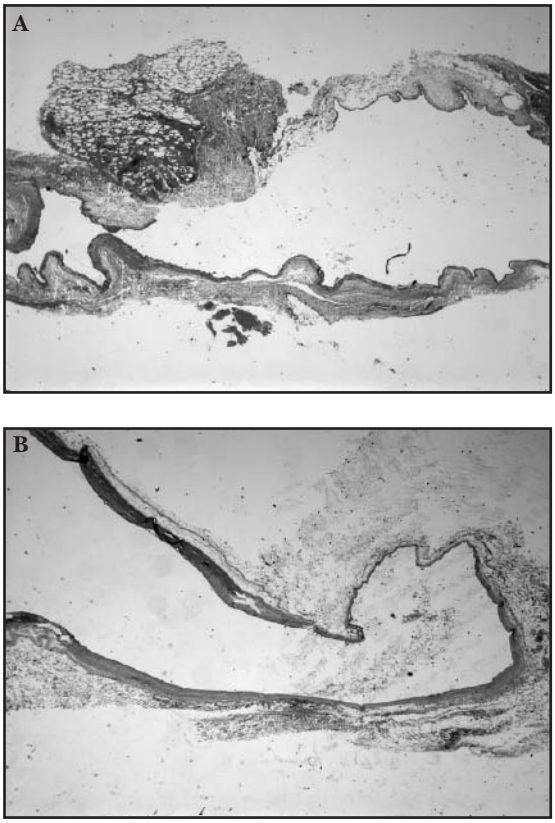

Fig. 3
While there was evidence of acute inflammation and tissue repair at two weeks (A) around both vitamin E impregnated and control polyethylene implants, by twelve weeks (B) there was a stable synovial-like membrane around all plugs with no signs of inflammation or foreign body reaction.

Study Two[4]

Materials and Methods

Massachusetts General Hospital

The second study used a canine model where a complete hip system was implanted in each dog. The acetabular liner was a highly crosslinked, vitamin E infused UHMWPE coupled with a CoCr head. The control liners were highly crosslinked and remelted UHMWPE. The animals were sacrificed at 12 weeks and histology sections were taken and analyzed by a pathologist.

Results

- No discernible difference in the local tissue response surrounding the control or the vitamin E infused polyethylene components.
- Noted variations in histological observations were not unique to either group and appear to represent normal variations in the tissue healing response.
- Vitamin E doped polyethylene acetabular components were well tolerated in the study with no adverse tissue reaction.

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Conclusion

Biomet continues to build on its legacy of high quality polyethylene by making incremental improvements in the manufacturing process based on sound engineering and science. The E1™ Antioxidant Infused bearings developed by Biomet, utilize cutting edge vitamin E technology invented at Massachusetts General Hospital. With its superior oxidation resistance, good mechanical properties and increased resistance to wear, E1™ Antioxidant Infused Material surpasses the limitations of remelted and annealed polyethylenes.[1]

Reference

1. Data on file at Biomet. Bench test results not necessarily indicative of clinical performance.

Notes

Notes

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