Background

Hip replacement is being performed on younger patients who expect to remain active throughout their lives, and this demographic shift has created a need for long-term implant bearing performance. In recent years, metal-on-metal hip constructs were increasingly adopted; however, this articular surface combination is associated with conditions including ion generation. As a result, surgeons are now showing a preference for highly crosslinked polyethylene (HXPE) liners, often in combination with a ceramic ball head, for their younger patients. First introduced in the 1990s, some HXPE liners demonstrated promising wear properties through the first decade of in vivo use. Recent studies have shown the potential for in vivo oxidation, which can affect long-term performance, performance in the second and third decades of use is not known. After years of research and development, Zimmer has addressed the issue of in vivo oxidation with a proprietary method of grafting (locking) Vitamin E to HXPE that prevents oxidation. The result is Vivacit-E Vitamin E Highly Crosslinked Polyethylene, a polyethylene hip liner that delivers on the three critical performance characteristics of polyethylene:

1. Exceptional oxidative stability
2. Ultra-low wear
3. Improved strength

Methods

Using classical material development strategy based on processing, microstructure and property relationships, Zimmer determined that an antioxidant-stabilized polyethylene could deliver long-term performance. After significant research, Zimmer selected the antioxidant Vitamin E and developed a process that results in exceptional oxidative stability, ultra-low wear and improved strength. The optimal quantity of Vitamin E is blended into the polyethylene powder to achieve a tightly controlled, homogeneous concentration throughout the material. Warm e-beam irradiation is then applied to the Vitamin E polyethylene blocks with a dose comparable to clinically proven Longevity® HXPE. The irradiation dose grafts (locks) Vitamin E directly to the polyethylene chain for long-lasting oxidative stability and forms crosslinks resulting in ultra-low wear.

Results

Vivacit-E HXPE underwent extensive testing to prove the material’s long-term performance advantages over the current best-in-class materials. Both remelted HXPE and gamma-irradiated conventional polyethylene failed prior to ten weeks of accelerated aging. In contrast, Vivacit-E HXPE prevented oxidation and maintained mechanical properties after 24 weeks of accelerated aging testing, a test length 12 times the industry standard. Simulator testing proved that Vivacit-E HXPE has a 96% improvement in wear vs. gamma-irradiated conventional polyethylene, as well as comparable wear to Longevity HXPE. Mechanical testing also proved that Vivacit-E HXPE improves upon the strength of remelted HXPE and maintains the strength of gamma-irradiated conventional polyethylene.

Conclusions

The increased utilization of total joint arthroplasty on a younger patient population has challenged the orthopedic industry to develop implants designed for long-term performance. Vivacit-E HXPE is designed to meet the long-term performance needs of the most demanding patients by grafting (locking) Vitamin E directly to highly crosslinked polyethylene. The result is a polyethylene articulating surface material that delivers exceptional oxidative stability, ultra-low wear and improved strength for long-term in vivo performance.
Introduction

Younger and More Demanding Patient Population

Joint replacement is occurring in increasingly younger patients (Figure 1) with over one-fifth of primary hip replacement procedures in the United States occurring in patients 55 years of age or younger. This younger patient population expects to remain active throughout their lives, creating a need for longer-lasting and higher-performance implants.

Metal on Metal Technology Utilization on High Demand Patients

High demand patients require hip implants that offer excellent performance characteristics including joint stability, wear properties, mechanical properties and improved aging properties. The orthopedic industry has repeatedly innovated articulating surface technology in an attempt to realize these performance characteristics (Figure 2). In the 2000s, Metal-on-Metal (MoM) hip constructs were widely adopted by surgeons treating young and active patients due to their promise of long-term durability, low wear and improved joint stability provided by large articulation sizes. The MoM market peaked at 37% of US total hip procedures in 2007, but has declined to minimal usage due to concerns related to metal ion release. The rise and fall of MoM indicates a demand for implants designed for young and active patients, a demand that is currently unmet.

Highly Crosslinked Polyethylene Utilization on High Demand Patients

The decline of MoM has prompted many surgeons to utilize highly crosslinked polyethylene (HXPE) with ceramic heads for high demand patients. HXPE was developed in the 1990s to reduce polyethylene wear and subsequent osteolysis that impacted clinical performance in previous generations of conventional polyethylene. A six center study led by Massachusetts General Hospital indicated that Zimmer’s Longevity and Durasul® remelted highly crosslinked polyethylene hip implants have worked as predicted, with ultra-low in vivo wear at 12 years follow up. These low wear rates in HXPEs provide confidence to surgeons utilizing larger diameter 36mm and 40mm articulations, which improve joint stability and reduce dislocation risks.

The clinical success of HXPE has been tempered by recent studies showing oxidation in explanted liners and increased in vivo wear. Oxidation is a primary mechanism of aging in polyethylene that leads to increased wear and decreased strength. Two potential causes of oxidation in vivo are the absorption of readily oxidizing lipids and the creation of free radicals during cyclic loading experienced in everyday activity. It is not known if the reported oxidation and higher wear rates of larger diameter heads will impact clinical performance after longer periods in vivo, but the data suggests a need to reevaluate bearing technology for young, active patients seeking performance well beyond the first decade.

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970s</td>
<td>Conventional UHMWPE first used as articulating hip liner</td>
</tr>
<tr>
<td>1980s</td>
<td>Conventional UHMWPE gamma sterilized in inert environment for oxidative stability</td>
</tr>
<tr>
<td>1990s</td>
<td>Highly Crosslinked Polyethylene for wear resistance</td>
</tr>
<tr>
<td>2000s</td>
<td>Peak of Metal-on-Metal for high demand patients</td>
</tr>
<tr>
<td>2010s</td>
<td>Vivacit-E Vitamin E HXPE for long-term performance in high demand patients</td>
</tr>
</tbody>
</table>

Figure 2. History of articulating surface technology for total hip replacement.
**Vivacit-E Vitamin E HXPE, a Solution for High Demand Patients**

To meet the need for longer-lasting hip implants, Zimmer addresses oxidation through a proprietary process that grafts (locks) the antioxidant Vitamin E to highly crosslinked polyethylene.\(^{14-19}\) The result is *Vivacit-E* Highly Crosslinked Polyethylene (HXPE), a hip liner material that delivers on the three characteristics required for long-term polyethylene performance: exceptional oxidative stability, ultra-low wear and improved strength (Figure 3).\(^{8-13}\)

**Foundation of Antioxidant-Stabilized Polyethylene**

Oxidative stability is one of the primary drivers of polyethylene’s long-term clinical performance.\(^{3-7}\) Irreversible and progressive oxidation occurs when free radicals, created during irradiation crosslinking or *in vivo* cyclic loading during normal activity, come in contact with oxygen. This oxidation process results in decreased mechanical properties and increased wear. In order to prevent oxidation, free radicals must be quenched before they can react with oxygen.\(^{25}\) This is the role of an antioxidant.

**Selecting the Right Antioxidant**

Zimmer researched and tested over 30 different antioxidants based on their ability to prevent oxidation, manufacturability and biocompatibility. Vitamin E was selected for its strong antioxidant properties. As a dietary supplement, the human body naturally utilizes Vitamin E to protect cell membranes from oxidation.\(^{25}\) To ensure antioxidant effectiveness, Zimmer uses d/l alpha tocopherol, a high purity synthetic Vitamin E commonly used in dietary supplements, fortified foods and cosmetic products.

**How Vitamin E Works**

The antioxidant activity of Vitamin E (alpha-tocopherol) is created by hydrogen donation from the hydroxyl (OH) group on the chroman ring to a free radical on the polyethylene chain as shown in Figure 4.

When Vitamin E is incorporated into polyethylene, it continuously quenches free radicals so that they do not react with oxygen. This prevents the oxidation cycle and the subsequent degradation of polyethylene. A critical amount of Vitamin E is required to continuously prevent polyethylene oxidation.\(^{25}\)

**Processing Vitamin E Polyethylene for Optimized Performance**

**Blending vs. Soaking**

There are two common methods used to incorporate Vitamin E into Ultra High Molecular Weight Polyethylene (UHMWPE). The first method is called “soaked” or “infused”. In this process, crosslinked polyethylene blocks are soaked in Vitamin E at a slightly elevated temperature for several hours (approximately 120°C). The Vitamin E-coated blocks are then placed into an inert oven and homogenized (baked) at 120°C until the Vitamin E diffuses through the thickness of the block. The physical infusion of Vitamin E can result in a non-uniform distribution within the polyethylene matrix, which can cause uneven material properties. A Fourier Transform Infrared Spectrometer lab instrument (FTIR) was used to identify and study the chemical composition of a Biomet E1 soaked Vitamin E liner. This analysis showed a highly non-uniform distribution of Vitamin E across the liner thickness, demonstrating the difficulty of achieving Vitamin E uniformity with the soaking method.\(^{26}\)

The second method, “blending”, involves mixing Vitamin E into polyethylene powder prior to compression molding. The resulting solid, Vitamin E-infused polyethylene blocks are then irradiation crosslinked. The Vitamin E is combined with the starting powder, a very uniform distribution of Vitamin E can be achieved throughout the
polyethylene. The blending process also allows for the Vitamin E concentration to be tightly controlled; this is important because a sub-optimal Vitamin E concentration can negatively affect material properties as well as the duration of oxidative stability. FTIR analysis shows that a tightly controlled, homogenous concentration of Vitamin E is achieved across the Zimmer Vivacit-E HXPE material.27

**Vivacit-E HXPE Manufacturing Process**

After significant research and consideration of both the soaking and blending processes, Zimmer pursued a proprietary blending process designed to maximize oxidative stability, minimize wear and improve mechanical properties (Figure 5). Vitamin E is blended directly into the polyethylene powder to achieve a tightly controlled, homogenous concentration throughout the Vivacit-E HXPE material. Warm e-beam irradiation is then applied with an effective dose comparable to that used for clinically proven Longevity HXPE.2 The irradiation grafts (locks) Vitamin E directly to the polyethylene chain for long-lasting oxidative stability and forms crosslinks resulting in ultra-low wear properties.9-11,14-19 The presence of Vitamin E in the polyethylene has the added benefit of eliminating the need to remelt the material after crosslinking to achieve oxidative stability, which results in improved mechanical strength.12,13

**Biocompatibility**

While HXPE and Vitamin E have been proven to be biocompatible with the human body, it is important to demonstrate the biocompatibility of any new implantable device. In order to prove Vivacit-E HXPE’s biocompatibility, extensive testing was performed according to International Organization for Standardization (ISO)10993 standards (Figure 6). Vivacit-E HXPE passed all tests, showing benign inflammatory response and no local toxicity effects.28,38

**ISO 10993 Biocompatibility Tests**

<table>
<thead>
<tr>
<th>ISO Standard/Test Description</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>10993-5 Cytotoxicity</td>
<td>No evidence of causing cell lysis or toxicity</td>
</tr>
<tr>
<td>10993-11 Acute Systemic Toxicity</td>
<td>No evidence of systemic toxicity</td>
</tr>
<tr>
<td>10993-10 Max Sensitivity</td>
<td>No evidence of causing delayed dermal contact sensitization</td>
</tr>
<tr>
<td>10993-10 Intracutaneous</td>
<td>Met all requirements of the test</td>
</tr>
<tr>
<td>10993-3 Genotoxicity</td>
<td>Did not induce micronuclei</td>
</tr>
<tr>
<td>10993-11 (13) Week Systemic Toxicity</td>
<td>No evidence of systemic toxicity</td>
</tr>
<tr>
<td>10993-6 (2) and (12) Week Muscle Implantation</td>
<td>Classified as a non-irritant</td>
</tr>
<tr>
<td>10993-11 (26) Week Systemic Toxicity</td>
<td>Classified as a non-irritant</td>
</tr>
</tbody>
</table>

**Biological Response to Wear Debris**

In addition to the ISO 10993, the biological response to wear debris generated by Vivacit-E HXPE was evaluated in an animal study. This data was submitted to the FDA and BSI in order to demonstrate the biocompatibility of the material. Billions of wear particles were injected into each rabbit knee joint and the animals were sacrificed after 3 and 6 months. The biological response to the wear particles was assessed locally and systemically by clinical observations, body weights, hematology, macroscopic observations at necropsy and histological evaluations of tissues and organs such as kidneys and lymph nodes. Vivacit-E HXPE particles did not elicit adverse biological reactions and Vivacit-E HXPE was classified as a non-irritant.28,29

**Grafting: Bonding of Vitamin E to Polyethylene**

Zimmer’s proprietary process efficiently grafts (locks) 75-90% of the Vitamin E to the polyethylene with covalent bonds, or the chemical link of two atoms through the sharing of electrons. A high level of grafting ensures that the optimal concentration of Vitamin E will be retained in the material to prevent oxidation.18,19
The soaking method does not result in grafting during irradiation crosslinking, as the soaking process happens after the irradiation dose. Vitamin E that is not grafted to the polyethylene has the potential to elute out of the material under the load and motion experienced in vivo.27

Irradiation Process: Gamma vs Zimmer’s E-Beam Process

All non-Zimmer HXPEs use gamma irradiation for crosslinking. A lower-energy irradiation source, gamma requires hours to achieve the target dose for HXPEs. Since it is not possible to keep the polyethylene at an elevated temperature throughout the process, gamma irradiation does not permit warm irradiation.

In contrast, e-beam delivers a high-energy stream of electrons to achieve the target dose in seconds, allowing the polyethylene to be irradiated at an elevated temperature. Only Zimmer’s proprietary e-beam irradiation process allows for warm irradiation. As previously mentioned, Vitamin E grafting is achieved through high dose, warm e-beam irradiation. Research by Massachusetts General Hospital, shown in Figure 7, demonstrates a significant increase in the percentage of grafted Vitamin E through warm versus cold irradiation.14

Grafting Prevents Vitamin E Elution for Long-Term Prevention of Oxidative Aging

To prove that grafting prevents elution of Vitamin E, aggressive extraction testing was performed to purposefully remove the Vitamin E using both polar and non-polar solvents. Even under these extreme extraction methods, well beyond in vivo conditions, the extracted materials contain no Vitamin E (Figure 8). This testing proved that Vitamin E is retained in Vivacit-E HXPE.41

Figure 7. Increased Vitamin E grafting of warm irradiated Vitamin E HXPE over cold irradiated Vitamin E HXPE.14

Figure 8: FTIR spectrum for hexane doped with neat Vitamin E (top) and hexane residue after attempted extraction of 0.30 wt.% Vitamin E HXPE sample (bottom). The arrow indicates the characteristic Vitamin E peak produced by the neat Vitamin E in hexane. The hexane residue from the Vitamin E HXPE sample does not exhibit a peak, showing that Vitamin E was not extracted from the samples.14

Exceptional Oxidative Stability

Vivacit-E HXPE Prevents Oxidation and Maintains Performance Properties After Extended Accelerated Aging

The exceptional oxidative stability of Vivacit-E HXPE was proven through aggressive accelerated aging tests. As previously mentioned, oxidation is a primary mechanism of aging in polyethylene that results in decreased mechanical properties and increased wear.25 Vivacit-E HXPE underwent accelerated aging in a pure oxygen atmosphere in accordance with American Society for Testing and Materials (ASTM) F2003.8 This extreme aging is intended to force oxygen into the material and induce oxidation.

Tensile testing measures the tension or stretching force where a material undergoes permanent deformation and the tension force at which the material fails. Figure 9 shows the percent retention of tensile strength for unaged and aged samples of Vivacit-E HXPE, remelted HXPE and gamma-irradiated conventional polyethylene. Gamma-irradiated conventional polyethylene dramatically decreases in tensile strength after four weeks of accelerated aging. As expected, there is a significant delay in mechanical property degradation of the remelted polyethylene. Vivacit-E HXPE exhibits a negligible decrease in tensile strength after 24 weeks of aggressive aging and no measurable oxidation. This test proves that the Vitamin E in Vivacit-E HXPE actively and continuously prevents oxidation during extreme oxidative challenge.8
Resistance to Cracking Under Cyclic Stress in Oxidative Environment

*In vivo* oxidation can occur due to mechanical and/or cyclic loading and can lead to fracturing of the polyethylene. In order to evaluate resistance to environmental stress cracking, gamma-irradiated conventional polyethylene, remelted HXPE and *Vivacit*-E HXPE materials were subjected to a bending stress of 10 MPa at a frequency of 0.5 Hz in air at 80°C. Gamma-irradiated conventional polyethylene and remelted HXPE oxidized and cracked prior to completion of the 1.5 million cycle test. In contrast, *Vivacit*-E HXPE did not crack and showed negligible oxidation for the prescribed 1.5 million cycles of testing as shown in Figure 10.40

*Vivacit*-E HXPE absorbs significantly less lipid fluid than either gamma-irradiated conventional polyethylene or remelted HXPE. The exact mechanism by which Vitamin E reduces fluid absorption is not well understood, but it is most likely due to Vitamin E occupying free volume in the polyethylene, in turn reducing the space that can be occupied by the lipid environment. Since the Vitamin E in *Vivacit*-E HXPE is grafted to the polymer after irradiation, it is resistant to displacement by the lipid environment.42

Figure 12 shows the oxidation due to lipid absorption of gamma-irradiated conventional polyethylene, remelted HXPE and *Vivacit*-E HXPE as a function of time. Each material underwent accelerated aging, followed by 5Mc wear testing in a lipid environment, followed by a second accelerated aging cycle. Absorption of readily-oxidizing lipids during wear testing made the remelted HXPE and gamma-irradiated conventional polyethylene susceptible to oxidation during an accelerated aging cycle. However, after three rounds of accelerated aging, followed by 5Mc wear simulator testing, followed by additional aging, *Vivacit*-E HXPE showed no oxidation (oxidation indices < 0.02). This proves that *Vivacit*-E HXPE prevents oxidation due to lipid absorption.43

Prevents Oxidation-Inducing Lipid Absorption

Highly crosslinked polyethylenes were developed to maintain long-term oxidative stability on the shelf and *in vivo*. Recent retrieval studies are showing signs of oxidation in HXPE materials that were originally thought to be permanently stabilized.3,6 Oxidation index values greater than 1.5 have been correlated to the loss of mechanical properties, which may lead to fatigue damage *in vivo*.47 Figure 11 shows the oxidation of a four year old Stryker X3 retrieval, with a maximum oxidation index above 1.4.

The unexpected oxidation in the Styker X3 implant was likely produced by *in vivo* oxidation of absorbed lipids or free radicals generated during cyclic loading. Lipids readily enter into oxidation reactions when they come in contact with free radicals, creating a need to understand polyethylene lipid absorption.
Ultra–Low Wear

*Vivacit-E* HXPE’s predecessor, *Longevity* HXPE, demonstrates ultra-low wear performance both clinically and in simulator testing. To obtain similar crosslink density and wear performance, *Vivacit-E* HXPE has the same effective e-beam irradiation dose as *Longevity* HXPE. *Vivacit-E* HXPE showed a 96% reduction in wear compared to gamma-irradiated conventional polyethylene (Figure 13) and comparable wear to clinically proven *Longevity* HXPE in standard 5 million cycle wear simulator testing. To prove *Vivacit-E* HXPE’s long-term ultra-low wear properties, a simulator test was run to 45 million cycles (Figure 14). The test proved *Vivacit-E* HXPE has very low wear even after long-term simulator testing.44

Wear Properties Maintained After Accelerated Aging

Oxidation of polyethylene leads to increased wear.5-7 To prove that the wear properties of *Vivacit-E* HXPE are maintained after oxidative aging, *Vivacit-E* HXPE liners were aged for 2 and 6 weeks (ASTM F2003) and subjected to wear simulator testing according to ISO 14242 protocol for 5 million cycles. The volumetric wear rates for 2- and 6-week aged *Vivacit-E* HXPE are statistically equivalent and demonstrated 96% improvement over 2-week aged gamma-irradiated conventional polyethylene (Figure 15).9

Figure 12. Comparison of gamma-irradiated conventional polyethylene, remelted HXPE and *Vivacit-E* HXPE oxidative index after accelerated aging, wear simulator testing followed by 6 weeks of additional ambient air aging.43 Oxidation Index values above 1.5 have been correlated to the loss of mechanical strength, which may lead to fatigue damage *in vivo*.47

Figure 13. 12 station AMTI hip simulator in accordance with ISO 14242-1.9-11

Figure 14. 12 station AMTI hip simulator in accordance with ISO 14242-1. Gamma-irradiated conventional polyethylene data beyond 5 Mc is extrapolated.44

Figure 15. Wear simulator testing showing no statistical difference between 2 week aged and 6 week aged *Vivacit-E* liners. 12 station AMTI hip simulator in accordance with ISO 14242-1.9
**Improved Strength**

The remelting process in *Longevity* HXPE is designed to provide oxidative stability, but results in a slight reduction of mechanical strength. Since *Vivacit-E* HXPE is stabilized with Vitamin E and not remelted, it retains the strength of gamma-irradiated conventional polyethylene, as shown in Figures 16 and 17. Due to *Vivacit-E* HXPE's continuous prevention of oxidative aging, the strength of the material is maintained even after extreme accelerated aging.8,12,13

![Diagram](image)

**Figure 16.** Comparison of Ultimate Tensile Strength.12, 13

**Figure 17.** Comparison of Tensile Yield Strength.12, 13

**Anatomic Fatigue Testing**

*Vivacit-E* HXPE liners were subjected to clinically relevant forces simulating daily living activities. Neutral and elevated-rim *Vivacit-E* HXPE liners were fatigue-loaded at orientations representing cup placement angles of 20°, 40° and 60° of inclination with 20° of anteversion. All liners completed fatigue testing without evidence of fracture (Figure 18).45

![Diagram](image)

**Figure 18.** Anatomic fatigue testing at inclinations of 20°, 40° and 60° and 20° of anteversion.

**Aged and Unaged Small Punch Results Demonstrating *Vivacit-E* HXPE Strength Advantage Over Stryker X3 Liners**

Small punch testing has emerged as a method of characterizing polyethylene mechanical properties and has the advantage of allowing testing on finished components due to the small size of test specimens. Small punch testing measures mechanical properties by looking at the deformation of small discs under loading conditions. Results are characterized by a load-displacement curve that provides total energy to failure (total area under the load-displacement curve), peak load, ultimate load and maximum displacement. Researchers have demonstrated a dependence on the area under the load-displacement curve to wear results of the material.25

Small punch testing was conducted on both unaged and aged Stryker X3 liners and *Vivacit-E* HXPE liners to compare the impact of aging on each material's mechanical properties. The Stryker X3 samples, lacking an antioxidant, show a 54% to 68% loss in mechanical properties when accelerated aged to 2 and 4 weeks, and had a total energy to failure after 4 weeks of aging that was 2.4 times less than 4-week aged *Vivacit-E* HXPE (Figure 19).

![Diagram](image)

**Figure 19.** Representative small punch curves for aged Stryker X3. Aging weeks are shown on the Figure.46
The *Vivacit-E* HXPE samples show no statistical change in properties over 33 weeks of accelerated aging (Figure 20). This proves the long-term strength advantage of *Vivacit-E* HXPE over Stryker X3 after accelerated aging.46

![Vivacit-E HXPE Small Punch Results](image)

**Figure 20.** Representative small punch curves for *Vivacit-E* HXPE. Specimens aged from 0-33 weeks. There is no statistical difference between the aged and unaged samples.46

**Conclusion**

The increased utilization of total hip arthroplasty in a younger patient population requires the orthopedic industry to develop implants designed for long-term performance. To meet this need, *Vivacit-E* HXPE was developed to be Zimmer’s longest-lasting and most durable polyethylene hip liner, delivering on the three critical performance criteria of polyethylene without compromise.

**Oxidative Stability**

*Vivacit-E* HXPE actively and continuously prevents oxidation by incorporating an optimal quantity of Vitamin E, which is grafted directly to the polyethylene. The result is a polyethylene hip liner with ultra-low wear and mechanical strength retention even after significant oxidative aging challenge.8

**Ultra-Low Wear**

High-dose e-beam irradiation results in *Vivacit-E* HXPE demonstrating a 96% wear reduction vs. gamma-irradiated conventional polyethylene and comparable ultra-low wear to clinically proven *Longevity* HXPE.9-11

**Improved Mechanical Strength**

*Vivacit-E* HXPE does not need to be remelted after crosslinking because the Vitamin E present in the material prevents oxidation. This results in *Vivacit-E* HXPE having superior mechanical strength compared to *Longevity* HXPE and improved tensile strength compared to gamma-irradiated conventional polyethylene.12,13
1. National Inpatient Sample, Hospital Cost and Utilization Project, Agency for Healthcare Research and Quality, US DHHS


7. Bohl JR, Bohl WR, Postak PD, Greenwald AS. The Coventry Award. The effect of shelf life on clinical outcome for gamma sterilized polyethylene

8. Zimmer ZRR_WA_2409_11

9. Zimmer ZRR_WA_2399_11

10. Zimmer ZRR_WA_2402_11, Rev. 1

11. Zimmer ZRR_WA_2512_12

12. Zimmer ZRR_WA_2401_11, Rev 1

13. Zimmer TM1140.98


18. Zimmer ZRM_WI_2410_11

19. Zimmer CRL 1202-080


26. Chemical Research Laboratory Test Number: 1207-016 and 1009-019

27. Zimmer ZRR_WI_2100_10

28. Report T1250_812

29. Report T1250_802

30. Report T0118_913/S

31. Report T0118_926

32. Report T0625_500

33. Report V0014_130

34. Report V0023_211

35. Report V0573_000/S

36. Report TO566_500

37. Report T1251_800

38. Report T1261_300


40. Zimmer ZRR_WA_2373_11

41. CPG Report 11622-1

42. Zimmer ZRR_WA_2587_12

43. CRL 1207-003

44. Zimmer Tribology Test Number: 1010-001.TTN

45. Zimmer ZRR_WA_2382_11

46. CPG report 11657 and 11650


NOTE: E1 is a trademark of Biomet. X3 is a trademark of Howmedica Osteonics (Stryker)

NOTE: Bench testing is not necessarily indicative of clinical performance.