



ELSEVIER

BASIC SCIENCE

The effect of vitamin E–enhanced cross-linked polyethylene on wear in shoulder arthroplasty—a wear simulator study



Justin J. Alexander, MBBS, FRACS^a, Simon N. Bell, MBBS, FRACS, PhD^{a,b,*}, Jennifer Coghlan, PhD^b, Reto Lerf, DSc^c, Frank Dallmann, Dipl-Ing^d

^aMelbourne Shoulder and Elbow Centre, Brighton, VIC, Australia

^bDepartment of Surgery, School of Clinical Sciences Monash Health, Monash University, Clayton, VIC, Australia

^cDepartment of Research and Development, Mathys Ltd Bettlach, Bettlach, Switzerland

^dDepartment of Research and Development, Mathys Orthopädie GmbH, Mörsdorf, Germany

Background: Wear of the polyethylene glenoid component and subsequent particle-induced osteolysis remains one of the most important modes of failure of total shoulder arthroplasty. Vitamin E is added to polyethylene to act as an antioxidant to stabilize free radicals that exist as a byproduct of irradiation used to induce cross-linking. This study was performed to assess the in vitro performance of vitamin E–enhanced polyethylene compared with conventional polyethylene in a shoulder simulator model.

Methods: Vitamin E–enhanced, highly cross-linked glenoid components were compared with conventional ultrahigh-molecular-weight polyethylene glenoids, both articulating with a ceramic humeral head component using a shoulder joint simulator over 500,000 cycles. Unaged and artificially aged comparisons were performed. Volumetric wear was assessed by gravimetric measurement, and wear particle analysis was also subsequently performed.

Results: Vitamin E–enhanced polyethylene glenoid components were found to have significantly reduced wear rates compared with conventional polyethylene in both unaged (36% reduction) and artificially aged (49% reduction) comparisons. There were no differences detected in wear particle analysis between the 2 groups.

Conclusion: Vitamin E–enhanced polyethylene demonstrates improved wear compared with conventional polyethylene in both unaged and artificially aged comparisons and may have clinically relevant benefits.

Level of evidence: Basic Science Study; Tribology

© 2019 Journal of Shoulder and Elbow Surgery Board of Trustees. All rights reserved.

Keywords: Vitamin E; wear; polyethylene; shoulder; arthroplasty

The Monash University Human Research Ethics Committee has approved this study.

*Reprint requests: Simon N. Bell, MBBS, FRACS, PhD, Melbourne Shoulder and Elbow Centre, 31 Normanby St, Brighton, VIC 3186, Australia.

E-mail address: snbell@bigpond.net.au (S.N. Bell).

Total shoulder arthroplasty has evolved over 4 decades to become a reliable procedure with satisfactory and predictable clinical outcomes and longevity.^{8,9,36,47,51} The glenoid remains the weak link in shoulder arthroplasty with

various modes of glenoid component failure still problematic.³³ Wear of the polyethylene glenoid component and subsequent particle-induced osteolysis is one of these modes of failure similar to what has been observed in hip and knee arthroplasty.^{27,33,40} Implant factors (component design, materials, and processing), surgeon factors (implant alignment, glenohumeral stability, and the presence of third body particles), and patient factors (rotator cuff function and activity levels) can all contribute to wear of the polyethylene glenoid component.^{2,14,15,26,27,33,43-45,49,50}

The role of vitamin E in polyethylene

The technique of cross-linking polyethylene arthroplasty components has been introduced in an attempt to reduce wear.²⁸ Ionizing radiation is used to induce molecular cross-linking but does lead to the creation of free radicals. These free radicals are the root of oxidative degradation, resulting in a reduction of mechanical qualities of the polyethylene, leading to a more brittle material prone to delamination and cracking.

Modern components are both sterilized and irradiated in oxygen-free environments, after which, postirradiation processes such as remelting or annealing are employed to reduce free radical concentration and improve oxidative stability. Concerns over the reduced mechanical properties seen in highly cross-linked polyethylene (XPE) after remelting or heat annealing, however, have led to the development of alternative methods to stabilize free radicals.¹⁶ Vitamin E (alpha-tocopherol) has been added to polyethylene to act as an antioxidant to stabilize free radicals that exist as a byproduct of irradiation, avoiding the reduction in toughness and fatigue strength caused by first-generation postirradiation techniques and also protecting against future *in vivo* oxidation. *In vitro* studies have demonstrated that significant oxidative resistance can be achieved by the addition of vitamin E.^{29,30,42} Biomechanical studies have shown improved wear compared with polyethylene without vitamin E, especially after accelerated aging.^{19,38,52}

Shoulder arthroplasty factors

Although the introduction of XPE (with or without vitamin E supplementation) in hip and knee arthroplasty has been well documented, there is little comparable literature in the shoulder.¹² It is important to study the shoulder independently rather than simply extrapolate results as it has been shown previously that shoulder arthroplasty behaves very differently to the hip in terms of wear patterns and particle generation.^{31,53}

The kinematics of a shoulder arthroplasty are more similar to a knee than a hip in that the articulation is noncongruent with resultant relative point-loading. There is

a combination of rolling and sliding motions, again similar to what is seen in knee arthroplasty, and it has been demonstrated that the subsequent wear particles are larger and more fibrillary compared with those generated in a hip arthroplasty.^{28,31,53}

Edge loading is a specific consideration that must be addressed when considering shoulder arthroplasty. The significant translation that occurs between the humeral head and the glenoid components results in rim contact and edge loading, with potentially detrimental effects on polyethylene glenoid components.^{1,32,54} Retrieval studies have shown that glenoid implants are rarely worn centrally, rather demonstrating delamination or peripheral damage.³ Although cross-linking is considered the main factor improving polyethylene wear in hip and knee arthroplasty, vitamin E enhancement may be of particular relevance in shoulder arthroplasty to maintain the elasticity of polyethylene over time in an edge loading scenario.^{19,29,30}

Aim

This study was performed to assess the *in vitro* performance of vitamin E-enhanced, highly cross-linked polyethylene (VE-XPE) compared with conventional ultrahigh-molecular-weight polyethylene (UHMWPE) in a shoulder simulation model. Both unaged and artificially aged components were tested to investigate the effect of vitamin E on oxidative degradation.

Materials and methods

Testing was carried out at an independent laboratory (IMA Material Research and Application Technology GmbH, Dresden, Germany).

Test specimens

The 4 test series are summarized in [Table I](#). All components are commercially available shoulder prostheses manufactured by Mathys Ltd. Bettlach (Switzerland). The control groups (TS1 and TS2) used UHMWPE size 4 glenoid components. The test groups (TS3 and TS4) used Vitamys polyethylene (VE-XPE) size 4 glenoid components. Vitamys is manufactured from GUR 1020 UHMWPE, contains 0.1% (by weight) blended vitamin E (alpha-tocopherol), and undergoes cross-linking by an irradiation dose of 70 kGy. All test cohorts used size 51/19 Affinis ceramic (Al₂O₃) humeral head components. The resultant radial mismatch between the humeral head and glenoid components was 4 mm. Each series comprised 3 specimens tested and 1 specimen as soak control.

The glenoid components of series TS2 and TS4 were artificially aged before the wear test. The accelerated aging was done according to ASTM F 2003.⁶ This treatment simulates shelf life or *in vivo* conditions equivalent to 10 years.⁵⁸

Table I Summary of the 4 test series

Test series	Component	Material
TS1	Glenoid	UHMWPE
	Humeral head	Ceramic (Al ₂ O ₃)
TS2	Glenoid	UHMWPE (aged)
	Humeral head	Ceramic (Al ₂ O ₃)
TS3	Glenoid	VE-XPE
	Humeral head	Ceramic (Al ₂ O ₃)
TS4	Glenoid	VE-XPE (aged)
	Humeral head	Ceramic (Al ₂ O ₃)

UHMWPE, ultrahigh-molecular-weight polyethylene; *VE-XPE*, vitamin E-enhanced highly cross-linked polyethylene.

Wear test method

The wear tests were performed by using the shoulder joint simulator “Shoulder III” according to IMA-PV C/33.3 and ISO 14 243-1.²² This wear simulation protocol was developed based on ISO standards and previously reported wear studies on shoulder prostheses with particular attention paid to translational movements and edge loading of the glenoid prosthesis.^{22,54}

For the test, the components were fastened in the adaptors and in the test rig. The glenoid component was positioned such that its vertical axis was at 45° to the *x*- and *y*-axes. The glenoid adaptor was mounted on a swing that allowed translational movement in both *x*- and *y*-directions. The load was applied vertically along the *z*-axis. The prostheses were submerged in a lubricant fluid (bovine serum solution) maintained at temperature 37°C ± 2°C by an external heating source.

The simulation completed 500,000 cycles of simulated arm motion incorporating angular movement around both the *x*- and *y*-axes. The movement around the *x*-axis and the *y*-axis is simulating adduction-abduction and arm forward flexion-extension. Additional translational movement along the *y*-axis was initiated (with guided edge loading ± 1.5 mm initiated by a horizontal actuator) to simulate rolling, sliding, and cross-shear mechanisms. The test parameters are described in detail in Table II, and the kinematic profile is demonstrated in Figure 1.

Analysis

Photo-optical documentation was completed on all specimens before and at the conclusion of testing.

Gravimetric measurements according to ISO 14242-2 and ISO 1206-2 were used to determine the amount of wear and the wear rate.^{21,24} To minimize the effect of fluid absorption in the case of polyethylene implants, components were presoaked according to ISO 14242-2 without axial load.²¹ During the test, the components were removed and weighed at defined intervals (0, 100,000, and 500,000 cycles). The mass of the tested components and the control specimen was measured. The accuracy of the calculated mass change is ±0.2 mg.

For the analysis of wear particles, separation of wear particles was performed using a polycarbonate filter of 0.1 µm pore size in accordance with ATSM F 561 and ISO 17853.^{7,23} The filters were

Table II Detailed test parameters for the shoulder wear test according to IMA-PV C/33.3

Parameter	Preconditioning period	Aging period
Packaging	Original packaging	Without packaging
Duration (d)	28	14
Environment	Ambient conditions	Pure oxygen
Temperature (°C)	23 ± 2	70 ± 2
Pressure	Normal room conditions	503 kPa

coated with gold and investigated under the scanning electron microscope. On each filter, 10 separate (no overlap) fields were appraised. The magnification of the micrographs was ×10,000 for the determination of relevant parameters. Particles >10 µm were appraised with a magnification of ×1000 to ×5000. The parameters used for the characterization of size and morphology of wear particles include equivalent circle diameter, area, elongation, aspect ratio, form factor, and roundness in accordance with ATSM F 1877.⁵

Results

Optical appearance

Before the test, the articulating surfaces were free from embedded particles, scratches, and score marks other than those arising from the finishing process. After the test, the glenoids showed a typical wear pattern. On the articulating surfaces the transition between loaded and unloaded regions was clearly visible. Evidence of wear around the rim of the prosthesis confirmed that edge loading had occurred during the simulation (Fig. 2). No backside wear was observed.

Gravimetric investigations

Mean wear rates for the 4 test series are summarized in Figure 3. The wear rate of unaged VE-XPE (TS3) was 9.97 ± 0.95 mg/10⁶ cycles compared with a wear rate of 15.54 ± 2.08 mg/10⁶ cycles for unaged UHMWPE (TS1). This is a 36% reduction in wear in the VE-XPE group and is statistically significant (*P* = .003).

Examining the 2 artificially aged cohorts, the wear rate of aged UHMWPE (TS2) was 26.44 ± 3.01 mg/10⁶ cycles compared with a wear rate of 13.61 ± 1.37 mg/10⁶ cycles in the aged VE-XPE (TS4). Compared with matched unaged cohorts, both aged cohorts demonstrated increased wear rates after artificial aging; however, the advantage of VE-XPE over UHMWPE is more pronounced with a 49% reduction in wear in the VE-XPE group (*P* = .0002).

Wear particle analysis

There were 2 typical types of wear particles observed. Figure 4 shows examples of both types of particles captured

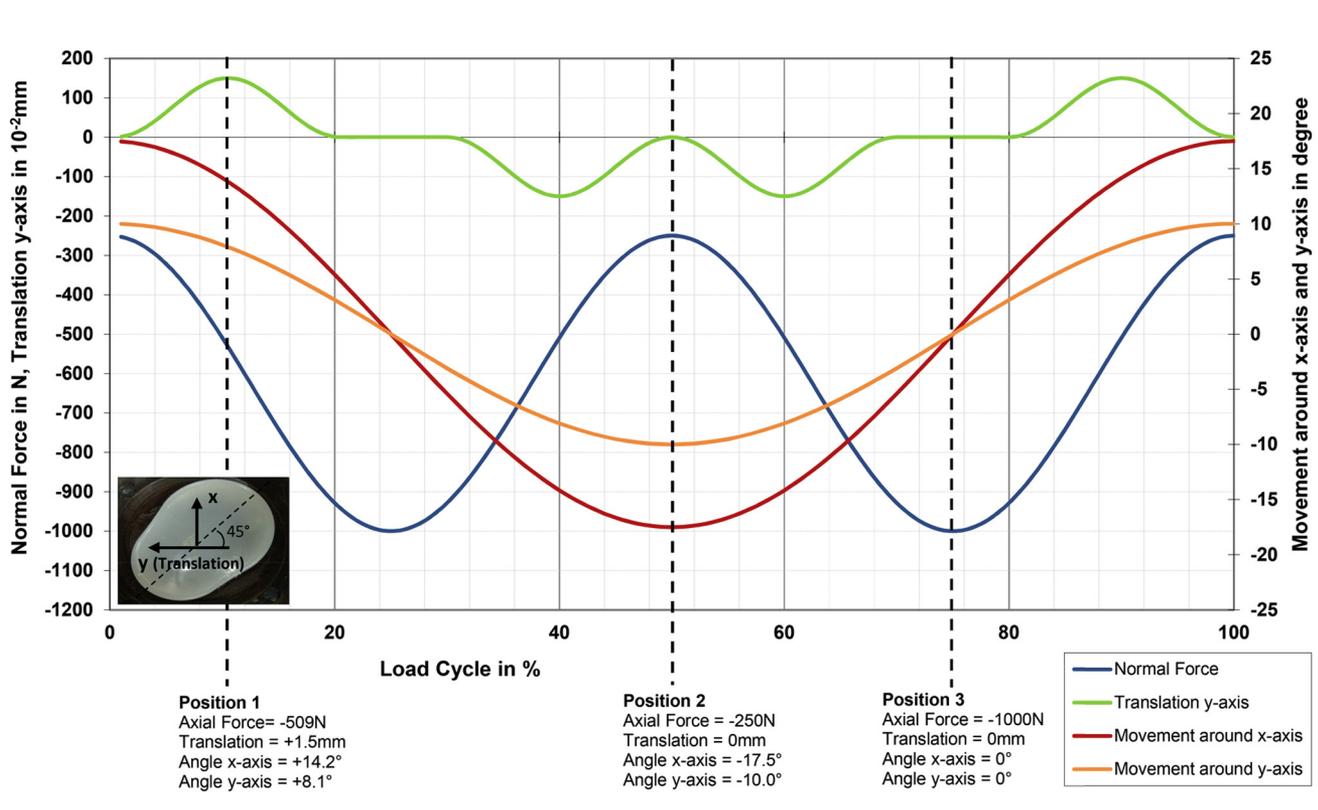


Figure 1 Kinematic profile for “Shoulder III” simulation demonstrating curves for load, angular movement, and displacement during a single cycle. The orientation of the glenoid component relative to the x - and y -axis is also demonstrated.

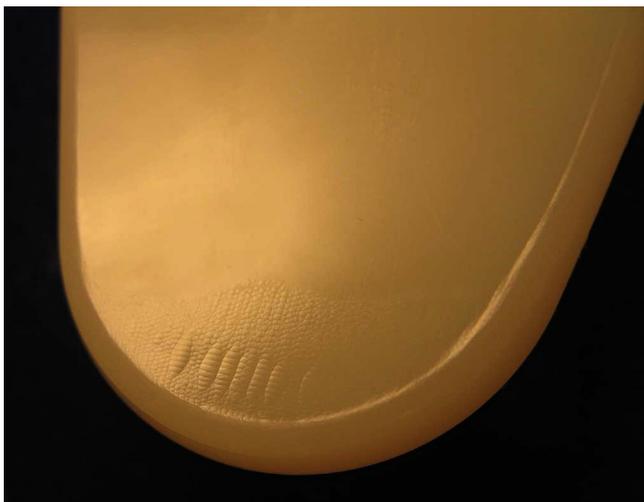


Figure 2 Photograph of the glenoid component after completion of testing demonstrating evidence of edge loading.

in the same micrograph. Type 1 wear particles are in the range up to $5\ \mu\text{m}$. Because these particles are important in terms of biological activity, they were analyzed in detail. Type 2 particles are larger, with sizes from $10\ \mu\text{m}$ up to $100\ \mu\text{m}$. These particles have not been included in the analysis of detailed morphology parameters.

Table III summarizes the results of the analysis of particle size and shape. The size and morphologic parameters of the particles are not significantly different between the 4 investigated test series. Further analysis of the distribution of particle sizes and morphology within each test series also did not reveal any significant differences.

Discussion

In this study, VE-XPE glenoid components demonstrated less wear than conventional polyethylene (UHMWPE) components in both unaged and artificially aged comparisons. Wear rates of all polyethylene components increased with artificial aging; however, the effect of aging was significantly less in the vitamin E-stabilized specimens. These findings suggest that, relative to conventional polyethylene, vitamin E-enhanced polyethylene has superior wear characteristics both at the time of implantation, and also long term as this advantage may persist or even be exaggerated because of resistance to *in vivo* oxidative degradation.

Analysis of wear particles demonstrated that particle size distribution and morphology was comparable between all test groups. It can be concluded that the specific biologic activity of these wear particles would therefore be

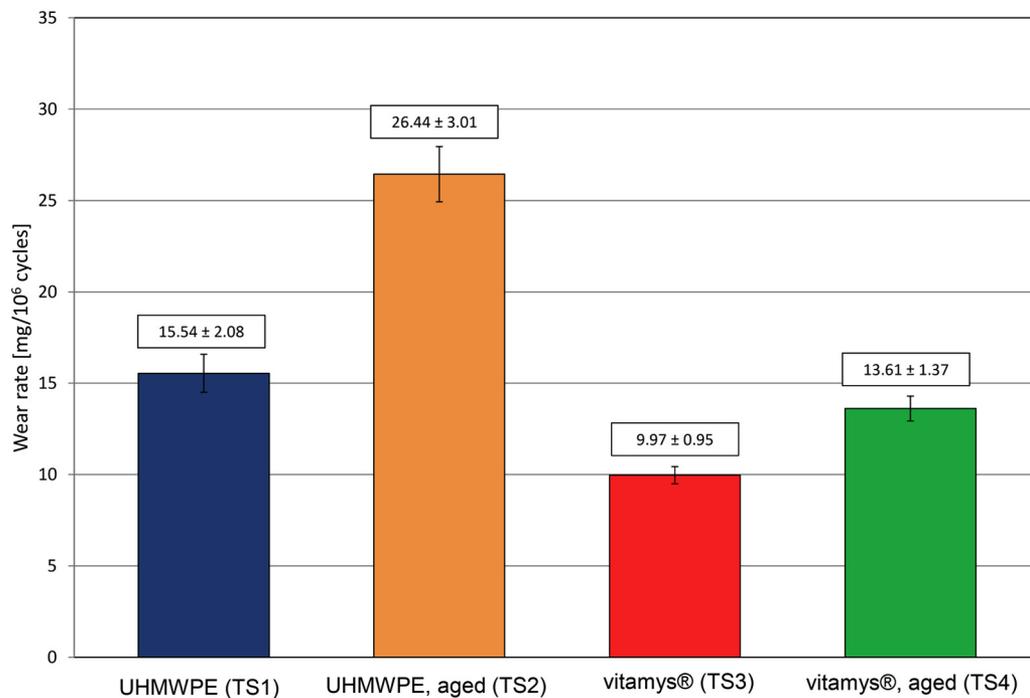


Figure 3 Gravimetric wear results for the 4 test series. *UHMWPE*, ultrahigh-molecular-weight polyethylene.

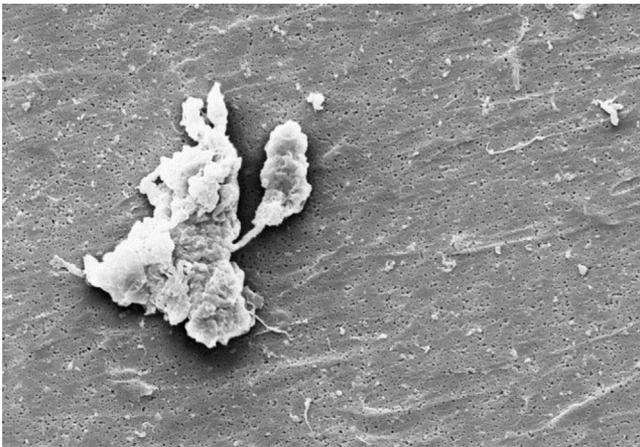


Figure 4 Photomicrograph demonstrating examples of type 1 (smaller) and type 2 (larger) wear particles.

comparable.¹³ Any difference in functional biological activity (calculated as the product of specific biological activity and volume of wear debris) between the groups would be purely due to differences in wear volume. Vitamin E polyethylene demonstrated reduced wear volume in both aged and unaged comparisons, and therefore reduced levels of wear particle-induced osteolysis can be expected with the use of these glenoid components.

Ceramic humeral heads have been used for fracture shoulder prostheses since 2000 and more recently for elective shoulder prostheses since 2009. The shift from a metal to ceramic humeral head component has been

supported predominantly by results from total hip arthroplasty (both in vitro and in vivo).^{8,11,41} A recent publication demonstrated a 27% reduction in wear rate using a ceramic head compared with a metallic head in a shoulder simulator model.³⁵

The introduction of a second innovation (ceramic head) in addition to the studied variable (VE-XPE) may be considered a limitation of this study. It is important to consider, however, that the ceramic humeral head component was consistent across all test cohorts and therefore will not affect comparisons between the groups. The use of ceramic heads is supported by the findings of Mueller et al³⁵ as well as the increasing use of ceramic humeral heads observed in the Australian National Joint Replacement Registry.⁸

In 2009, Wirth et al⁵⁴ published a paper comparing in vitro wear between conventional and highly cross-linked polyethylene in a shoulder simulator model. That study used a similar simulator protocol with consideration given to a combination of sliding, rolling, translation, and edge loading and demonstrated an 85% reduction in wear rate in the XPE group compared with conventional polyethylene. The wear rates between the XPE cohort in that study (7.0 mg/10⁶ cycles) and the vitamin E XPE cohort in our study (9.97 mg/10⁶ cycles) are comparable, especially when taking into account subtle differences in simulator protocols. Particle analysis was also undertaken as part of that paper and, as with our study, demonstrated no significant differences in particle size or morphology between the 2 polyethylene types.

Table III Size and morphologic measurements of analyzed wear particles

Parameter	Value		Comment
	Maximum	Minimum	
Normal force, F_z (N)	-1000	-250	z-direction
Movement around the y -axis, α_y (deg)	+10	-10	x -direction
Movement around the x -axis, α_x (deg)	+17.5	-17.5	y -direction
Movement in the y -direction, s_y (mm)	+1.5	-1.5	y -direction
Test frequency, f (Hz)	1		
Test medium	Bovine serum solution		
Protein content, (g/L)	30		
Test temperature, ($^{\circ}$ C)	37 ± 2		
Total number of cycles, N_{total}	5×10^5		
Time point of inspections	0		$3 \times$ routine inspections
	1×10^5		
	5×10^5		

Other papers specifically examining the wear properties of vitamin E-stabilized polyethylene in arthroplasty have all been performed using hip and knee simulator protocols. These were summarized in a review paper by Gigante et al.¹⁷ When compared with UHMWPE, VE-XPE demonstrates anywhere between 54% and 92% reduction in wear.^{1,18,19,34,37,46,48}

Only 2 studies have compared XPE with and without vitamin E, both in hip simulator models, and the results are somewhat conflicting. In a paper by Affatato et al.,¹ VE-XPE was found to have reduced wear characteristics due to reduced cross-linking density. It has also been shown, however, that when medium-low concentrations of vitamin E (0.1% wt.) are blended with polyethylene, the same cross-link density can be obtained by simply increasing the radiation dose. A subsequent paper by Grupp et al.¹⁸ demonstrated comparable wear rates between XPE and VE-XPE when a higher irradiation dose was used. This paper also examined the effect of artificial aging and demonstrated a 95% reduction in wear after prolonged aging of VE-XPE compared with XPE.

Similar to the paper by Wirth et al.,⁵³ the wear particles isolated from our study were similar in size, distribution, and morphology to those described in retrieval studies examining debris isolated from interface membranes at the time of revision shoulder arthroplasty, supporting the validity of our shoulder simulator model.^{31,53,54} Although the size and morphology characteristics of wear particles generated from VE-XPE are not different to those from UHMWPE, the biological effect of vitamin E must also be considered.

Even though vitamin E is a naturally occurring antioxidant fundamental to human metabolism, the biocompatibility of vitamin E polyethylene has been well studied. Multiple in vitro and animal studies have shown no adverse biological responses to vitamin E-stabilized polyethylene.^{25,55-57} Furthermore, 2 animal studies have shown that the osteolytic

response to wear particles from VE-XPE is equivalent or reduced compared with UHMWPE or XPE.^{10,20}

Being an in vitro study, discretion must be exercised in directly extrapolating the results to a clinical scenario. That said, a number of factors have been carefully considered in the design of this study (such as an emphasis on edge loading) to maximize its clinical relevance to shoulder arthroplasty.

The simulation protocol was run for 500,000 cycles, which is somewhat less than comparable studies, which have been performed out to 5 million cycles.^{39,54} There are no specific definitions in the shoulder standard regarding loading, cycles, and amount of wear for shoulder arthroplasty.⁴ The study group assessed 500,000 cycles as sufficient for wear evaluation, because the characteristic curve is straight after a short run-in within 100,000 cycles and stays straight lined over several million cycles. This was tested in prestudies and no additional information was seen up to 5 million cycles.

The comparison group in our study was UHMWPE rather than XPE. Although it might be argued that XPE has been shown to be the current gold standard in terms of wear, it was considered more important to keep the number of variables between our test cohorts to a minimum and the only available glenoid components of comparable geometry are made from UHMWPE.

Conclusion

This study suggests that the use of VE-XPE glenoid components in shoulder arthroplasty will reduce the rate of polyethylene wear. The benefits over UHMWPE are seen from the time of implantation due to superior mechanical wear characteristics, and those advantages are exaggerated in the long term because of enhanced

resistance to in vivo oxidative degradation. Given the reduced volume of wear particles, reduced osteolysis can be expected resulting in improved implant longevity.

Acknowledgment

We acknowledge Prof. Dr. Rainer Franke, IMA Material Research and Application Technology GmbH, Dresden, Germany, for statistical analysis.

Disclaimer

Simon N. Bell has a consultancy agreement with Mathys Ltd. Bettlach (Switzerland) and Wright Medical (Australia).

Frank Dallman is an employee of Mathys Orthopaedie GmbH (Germany).

Reto Lerf is an employee of Mathys Ltd. Bettlach (Switzerland).

Jennifer Coghlan receives funds for data collection, entry, and storage through her Department of Monash University, Australia from Mathys Bettlach (Switzerland), Mathys Australia, Wright Medical (Australia).

Justin J. Alexander, his immediate family, and any research foundations with which he is affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

References

- Affatato S, Bracco P, Costa L, Villa T, Quaglini V, Toni A. In vitro wear performance of standard, crosslinked, and vitamin-E-blended UHMWPE. *J Biomed Mater Res A* 2012;100:554-60. <https://doi.org/10.1002/jbm.a.33297>
- Anglin C, Wyss UP, Pichora DR. Mechanical testing of shoulder prostheses and recommendations for glenoid design. *J Shoulder Elbow Surg* 2000;9:323-31.
- Ansari F, Lee T, Malito L, Martin A, Gunther S, Harmsen S, et al. Analysis of severely fractured glenoid components: clinical consequences of biomechanics, design and materials selection on implant performance. *J Shoulder Elbow Surg* 2016;25:1041-50. <https://doi.org/10.1016/j.jse.2015.10.017>
- ASTM F 1378. Standard specification for shoulder prostheses. West Conshohocken, PA: Copyright ASTM International; 2012.
- ASTM F 1877. Standard practice for characterisation of particles. West Conshohocken, PA: Copyright ASTM International; 2005. reapproved 2010.
- ASTM F 2003-08. Standard practice for accelerate aging of ultra-high molecular weight polyethylene after gamma irradiation in air. West Conshohocken, PA: Copyright ASTM International; 2002. reapproved 2008.
- ASTM F 561. Standard practice for retrieval and analysis of medical devices, and associated tissues and fluids. West Conshohocken, PA: Copyright ASTM International; 2005. reapproved 2010.
- Australian Orthopaedic Association National Joint Replacement Registry (AOANJRR). Hip, Knee & Shoulder Arthroplasty: 2018 Annual Report. Adelaide: AOA; 2018.
- Bell SN, Coghlan JA. Short stem shoulder replacement. *Int J Shoulder Surg* 2014;8:72-5. <https://doi.org/10.4103/0973-6042.140113>
- Bichara DA, Malchau E, Sillesen NH, Cakmak S, Petur-Nielsen G, Muratoglu OK. Vitamin E-diffused highly cross-linked UHMWPE particles induce less osteolysis compared to highly cross-linked virgin UHMWPE particles in vivo. *J Arthroplast* 2014;29:232-7. <https://doi.org/10.1016/j.arth.2014.03.044>
- Clarke IC, Gustafson A. Clinical and hip simulator comparisons of ceramic-on-polyethylene and metal-on-polyethylene wear. *Clin Orthop Relat Res* 2000;379:34-40.
- Dion NT, Bragdon C, Muratoglu O, Freiberg AA. Durability of highly cross-linked polyethylene in total hip and total knee arthroplasty. *Orthop Clin North Am* 2015;46:321-7. <https://doi.org/10.1016/j.joc.2015.02.001>
- Fisher J, Bell J, Barbour PS, Tipper JL, Matthews JB, Besong AA, et al. A novel method for the prediction of functional biological activity of polyethylene wear debris. *Proc Inst Mech Eng H* 2001;215:127-32.
- Franklin JL, Barrett WP, Jackins SE, Matsen FA III. Glenoid loosening in total shoulder arthroplasty. Association with rotator cuff deficiency. *J Arthroplasty* 1988;3:39-46.
- Garreau De Loubresse C, Norton MR, Piriou P, Walch G. Replacement arthroplasty in the weight-bearing shoulder of paraplegic patients. *J Shoulder Elbow Surg* 2004;13:369-72. <https://doi.org/10.1016/j.jse.2004.01.019>
- Gencur SJ, Rimnac CM, Kurtz SM. Fatigue crack propagation resistance of virgin and highly crosslinked thermally treated UHMWPE. *Biomaterials* 2006;27:1550-7. <https://doi.org/10.1016/j.jse.2004.01.019>
- Gigante A, Bottegoni C, Ragone V, Banci L. Effectiveness of vitamin-E-doped polyethylene in joint replacement: a literature review. *J Funct Biomater* 2015;6:889-900. <https://doi.org/10.3390/jfb6030889>
- Grupp TM, Holderied M, Mulliez MA, Streller R, Jäger M, Blömer W, et al. Biotribology of a vitamin E-stabilized polyethylene for hip arthroplasty—influence of artificial ageing and third-body particles on wear. *Acta Biomater* 2014;10:3068-78. <https://doi.org/10.1016/j.actbio.2014.02.052>
- Haider H, Weisenburger JN, Kurtz SM, Rimnac CM, Freedman J, Schroeder DW, et al. Does vitamin E-stabilized ultra high molecular weight polyethylene address concerns of cross-linked polyethylene in total knee arthroplasty? *J Arthroplasty* 2012;27:461-9. <https://doi.org/10.1016/j.arth.2011.03.024>
- Huang CH, Lu YC, Chang TK, Hsiao IL, Su YC, Yeh ST, et al. In vivo biological response to highly cross-linked and vitamin e-doped polyethylene—a particle-induced osteolysis animal study. *J Biomed Mater Res B Appl Biomater* 2016;104:561-7. <https://doi.org/10.1002/jbm.b.33426>
- ISO 14242-2. Implants for surgery—wear of total hip joint prostheses: part 2. Methods of measurement. Geneva: ISO Copyright Office; 2009.
- ISO 14243-1. Implants for surgery—wear of total knee-joint prostheses: part 1. Loading and displacement parameters for wear-testing machines with load control and corresponding environmental conditions for test. Geneva: ISO Copyright Office; 2009.
- ISO 17853. Wear of implant materials—polymer and metal wear particles: isolation, characterization and quantification. Geneva: ISO Copyright Office; 2011.
- ISO 7206-2. Implants for surgery; partial and total hip joint prostheses: part 2. Articulating surfaces made of metallic, ceramic and plastics materials. Geneva: ISO Copyright Office; 2011.
- Jarrett BT, Cofske J, Rosenberg AE, Oral E, Muratoglu O, Malchau H. In vivo biological response to vitamin E and vitamin E-doped

- polyethylene. *J Bone Joint Surg Am* 2010;92:2672-81. <https://doi.org/10.2106/JBJS.I.00068>
26. Karelse A, Van Tongel A, Verstraeten T, Poncet D, De Wilde LF. Rocking-horse phenomenon of the glenoid component: the importance of inclination. *J Shoulder Elbow Surg* 2015;24:1142-8. <https://doi.org/10.1016/j.jse.2014.12.017>
 27. Kepler CK, Nho SJ, Bansal M, Ala OL, Craig EV, Wright TM, et al. Radiographic and histopathologic analysis of osteolysis after total shoulder arthroplasty. *J Shoulder Elbow Surg* 2010;19:588-95. <https://doi.org/10.1016/j.jse.2009.09.012>
 28. Kurtz SM, editor. *UHMWPE Biomaterials Handbook*. 3rd edition. Oxford: Elsevier, ISBN 9780323354356; 2016. p. 159.
 29. Kurtz SM, Dumbleton J, Siskey RS, Wang A, Manley M. Trace concentrations of vitamin E protect radiation crosslinked UHMWPE from oxidative degradation. *J Biomed Mater Res A* 2009;90:549-63. <https://doi.org/10.1002/jbm.a.32122>
 30. Lerf R, Zurbrugg D, Delfosse D. Use of vitamin E to protect cross-linked UHMWPE from oxidation. *Biomaterials* 2010;31:3643-8. <https://doi.org/10.1016/j.biomaterials.2010.01.076>
 31. Mabrey JD, Afsar-Keshmiri A, Engh G, Sychterz CJ, Wirth MA, Rockwood CA, et al. Standardized analysis of UHMWPE wear particles from failed total joint arthroplasties. *J Biomed Mater Res* 2002; 63:475-83. <https://doi.org/10.1002/jbm.10302>
 32. Massimini DF, Li G, Warner JP. Glenohumeral contact kinematics in patients after total shoulder arthroplasty. *J Bone Joint Surg Am* 2010; 92:916-26. <https://doi.org/10.2106/jbjs.h.01610>
 33. Matsen FA III, Clinton J, Lynch J, Bertelsen A, Richardson ML. Glenoid component failure in total shoulder arthroplasty. *J Bone Joint Surg Am* 2008;90:885-96. <https://doi.org/10.2106/JBJS.G.01263>
 34. Micheli BR, Wannomae KK, Lozynsky AJ, Christensen SD, Muratoglu OK. Knee simulator wear of vitamin E stabilized irradiated ultrahigh molecular weight polyethylene. *J Arthroplast* 2012;27:95-104. <https://doi.org/10.1016/j.arth.2011.03.006>
 35. Mueller U, Braun S, Schroeder S, Schroeder M, Sonntag R, Jaeger S, et al. Influence of humeral head material on wear performance in anatomic shoulder joint arthroplasty. *J Shoulder Elbow Surg* 2017;26: 1756-64. <https://doi.org/10.1016/j.jse.2017.05.008>
 36. Neer CS, Watson KC, Stanton FJ. Recent experience in total shoulder replacement. *J Bone Joint Surg* 1982;64:319-37.
 37. Oral E, Christensen SD, Malhi AS, Wannomae KK, Muratoglu OK. Wear resistance and mechanical properties of highly cross-linked, ultrahigh-molecular weight polyethylene doped with vitamin E. *J Arthroplast* 2006;21:580-91. <https://doi.org/10.1016/j.arth.2005.07.009>
 38. Oral E, Godleski Beckos CA, Lozynsky AJ, Malhi AS, Muratoglu OK. Improved resistance to wear and fatigue fracture in high pressure crystallized vitamin E-containing ultra high molecular weight polyethylene. *Biomaterials* 2009;30:1870-80. <https://doi.org/10.1016/j.biomaterials.2008.12.029>
 39. Peers S, Moravek JE Jr, Budge MD, Newton MD, Kurdziel MD, Baker KC, et al. Wear rates of highly cross-linked polyethylene humeral liners subjected to alternating cycles of glenohumeral flexion and abduction. *J Shoulder Elbow Surg* 2015;24:143-9. <https://doi.org/10.1016/j.jse.2014.05.001>
 40. Raiss P, Edwards TB, Deutsch A, Shah A, Bruckner T, Loew M, et al. Radiographic changes around humeral components in shoulder arthroplasty. *J Bone Joint Surg Am* 2014;96:e54. <https://doi.org/10.2106/JBJS.M.00378>
 41. Ranawat A, Meftah M, Klingenstein G, Yun RJ, Ranawat C. Long-term performance of ceramic and metal femoral heads on conventional polyethylene in young and active patients: a matched-pair analysis. *J Bone Joint Surg Am* 2013;95:1193-7. <https://doi.org/10.2106/JBJS.L.00432>
 42. Rowell SL, Oral E, Muratoglu OK. Comparative oxidative stability of α -tocopherol blended and diffused UHMWPEs at 3 years of real-time aging. *J Orthop Res* 2011;29:773-80. <https://doi.org/10.1002/jor.21288>
 43. Severt R, Thomas BJ, Tsentler MJ, Amstutz HC, Kabo JM. The influence of conformity and constraint on translational forces and frictional torque in total shoulder arthroplasty. *Clin Orthop Relat Res* 1993;292:151-8.
 44. Shapiro TA, McGarry MH, Gupta R, Lee YS, Lee TQ. Biomechanical effects of glenoid retroversion in total shoulder arthroplasty. *J Shoulder Elbow Surg* 2007;16(3 Suppl):S90-5. <https://doi.org/10.1016/j.jse.2006.07.010>
 45. Sperling JW, Antuna SA, Sanchez-Sotelo J, Schleck C, Cofield RH. Shoulder arthroplasty for arthritis after instability surgery. *J Bone Joint Surg Am* 2002;84:1775-81.
 46. Teramura S, Sakoda H, Terao T, Endo MM, Fujiwara K, Tomita N. Reduction of wear volume from ultrahigh molecular weight polyethylene knee components by the addition of vitamin E. *J Orthop Res* 2008;26:460-4. <https://doi.org/10.1002/jor.20514>
 47. Torchia ME, Cofield RH, Settergren CR. Total shoulder arthroplasty with the Neer prosthesis: long-term results. *J Shoulder Elbow Surg* 1997;6:495-505.
 48. Vaidya C, Alvarez E, Vinciguerra J, Bruce DA, DesJardins JD. Reduction of total knee replacement wear with vitamin E blended highly cross-linked ultra-high molecular weight polyethylene. *J Eng Med* 2011;225:1-7. <https://doi.org/10.1243/09544119JEIM774>
 49. Vavken P, Sadoghi P, von Keudell A, Rosso C, Valderrabano V, Müller AM. Rates of radiolucency and loosening after total shoulder arthroplasty with pegged or keeled glenoid components. *J Bone Joint Surg Am* 2013;95:215-21. <https://doi.org/10.2106/JBJS.L.00286>
 50. Walch G, Edwards TB, Boulahia A, Boileau P, Mole D, Adeleine P. The influence of glenohumeral prosthetic mismatch on glenoid radiolucent lines: results of a multicenter study. *J Bone Joint Surg Am* 2002;84:2186-91.
 51. Walch G, Young AA, Melis B, Gazielly D, Loew M, Boileau P. Results of a convex-back cemented keeled glenoid component in primary osteoarthritis: multicenter study with a follow-up greater than 5 years. *J Shoulder Elbow Surg* 2011;20:385-94. <https://doi.org/10.1016/j.jse.2010.07.011>
 52. Wannomae KK, Christensen SD, Micheli BR, Rowell SL, Schroeder DW, Muratoglu OK. Delamination and adhesive wear behavior of alpha-tocopherol-stabilized irradiated ultra high molecular weight polyethylene. *J Arthroplast* 2010;25:635-43. <https://doi.org/10.1016/j.arth.2009.04.005>
 53. Wirth MA, Agrawal CM, Mabrey JD, Dean DD, Blanchard CR, Müller MM, et al. Isolation and characterization of polyethylene wear debris association with osteolysis following total shoulder arthroplasty. *J Bone Joint Surg Am* 1999;81:29-37.
 54. Wirth MA, Klotz C, Deffenbaugh DL, McNulty D, Richards L, Tipper JL. Cross-linked glenoid prosthesis: a wear comparison to conventional glenoid prosthesis with wear particulate analysis. *J Shoulder Elbow Surg* 2009;18:130-7. <https://doi.org/10.1016/j.jse.2008.06.015>
 55. Wolf C, Lederer K, Bergmeister H, Losert U, Böck P. Animal experiments with ultra-high molecular weight polyethylene (UHMWPE) stabilised with α -tocopherol used for articulating surfaces in joint endoprostheses. *J Mater Sci Mater Med* 2006;17:1341-7. <https://doi.org/10.1007/s10856-006-0609-5>
 56. Wolf C, Lederer K, Müller U. Tests of biocompatibility of α -tocopherol with respect to the use as a stabilizer in ultrahigh molecular weight polyethylene for articulating surfaces in joint endoprostheses. *J Mater Sci Mater Med* 2002;13:701-5.
 57. Wolf C, Lederer K, Pfragner R, Schauenstein K, Ingolic E, Siegl V. Biocompatibility of ultra high molecular weight polyethylene (UHMWPE) stabilised with α -tocopherol used for joint endoprostheses assessed in vitro. *J Mater Sci Mater Med* 2007;18:1247-52. <https://doi.org/10.1007/s10856-006-0098-6>
 58. Zurbrugg D, Abt N. Comparison between in vivo aging, shelf and accelerated aging of UHMWPE based on the theory of oxidation kinetics. Poster session presented at 18th European Conference on Biomaterials; 2003. Oct. 1-4; Stuttgart, Germany.