How Tough? A Comparison of Antioxidant and Traditional UHMWPE

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Introduction:

Ultra-high molecular weight polyethylene (UHMWPE) is the only bearing surface available in the United States for total knee arthroplasty (TKA), though resin type, irradiation dose, heat treatments, and the addition of antioxidants vary between manufacturer and design. To allow patients to comfortably complete various activities of daily living, UHMWPE implants must withstand multiple body weights and last for a decade or longer, especially as the number of TKA patients under 65 grows. To ensure this, fracture resistance of UHMWPE is tested by a number of methods, including J-Integral fatigue testing, tensile testing (e.g. area-under-the-curve) and impact testing. Double Notch Izod (DNI) testing is the preferred ASTM standard for measuring the impact strength of UHMWPE given the extraordinary toughness of the material. Prior work has shown that results from crosslinked and conventional samples tested in this method correlate well with results from tensile toughness methods[1]. However, little work has been done to compare the relationship of tensile and impact toughness across different resin types or with the addition of antioxidants. In this study we consider the effects of resin type, GUR 1020 and GUR 1050, and antioxidants on the tensile and impact toughness of UHMWPE.

Objectives

- Determine whether resin type and the addition of antioxidants affects the relationship between tensile and impact toughness.
- Consider which factors most significantly influence the tensile and impact toughness of UHMWPE

Materials and Method

Materials:

- 4 sets of samples of UHMWPE (GUR 1050), 4 sets of UHMWPE (GUR 1020), and 5 sets of antioxidant UHMWPE (also GUR 1020) were prepared for each test, each set irradiated to the doses listed on the right (Table 1)

Material Type	Nominal Radiation Dose (kGy)	TVI 1370
GUR 1020	Virgin	-0.0016496
	75	0.02475815
	100	0.02941088
	200	0.04283848
GUR 1050	Virgin	-0.0015706
	25	0.015706
	50	0.0271575
	75	0.03597956
Antioxidant 1	115	0.03872385
Antioxidant 2	135	0.03741352
Antioxidant 3	100	0.03074528
Antioxidant 4	130	0.0434856

Table 1: Summary of FTIR analysis, divided into 3 groups, GUR 1020, GUR 1050, and GUR 1020 Antioxidant

Double Notch Izod Testing: (Impact Toughness)

- 10-17 Rectangular Prisms of each material milled to 2.5" x .5" x .25" and then notched using a vise and razor blade (Figure 3)
- Samples tested on Izod impact machine (5.5 J impact hammer, Resil Impactor, Ceast, Charlotte, NC)
- Area of cross section between notches of each sample measured using optical microscopy post testing
- Impact strength of each material calculated by dividing corrected energy (accounting for energy loss due to windage and friction) by area of cross section

Fourier Infrared Spectroscopy (FTIR) Analysis and Tensile Testing:

- Thin sections created by microtoming 200 um-thick sheets from each bulk material using sledge microtome (Reichert-Jung Poly Cut S microtome)
- ASTM Type V die used to punch tensile specimens with gauge length of 1cm
- 5 spots along the gauge length of each specimen were analyzed using FTIR (Thermo Scientific iN-10 FTIR microscope) to verify that the materials had not oxidized and to determine TVI, which directly correlates with irradiation dose

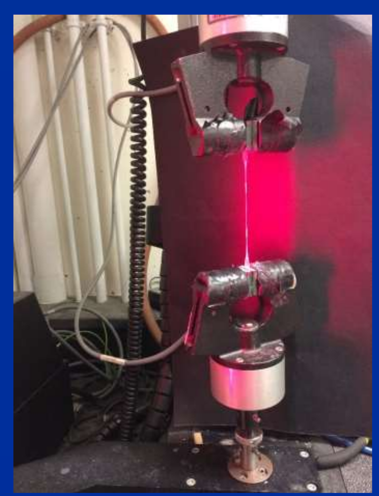

Figure 1: Tensile test, showing Instron grips and red light from optical extensometer

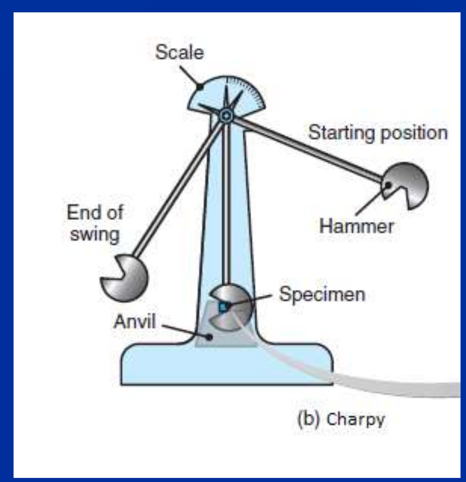

Figure 2: Diagram showing method used to measure impact toughness (Double Notch Izod)

Figure 3: Picture of notched specimen prepared for Double Notch Izod testing

- Samples were then tested on an electromechanical load frame (strain rate 100% per minute) (Instron 5544 load frame equipped with a 2-kN load cell, pneumatic sample grips, video extensometer)
- Toughness reported as work-to-failure, via the under the curve method *(Toughness = 1000*Energy(J)/[Gauge Length(mm) * Thickness(mm)* Width(mm)])*
- All values normalized to sample dimensions (e.g. width and thickness)

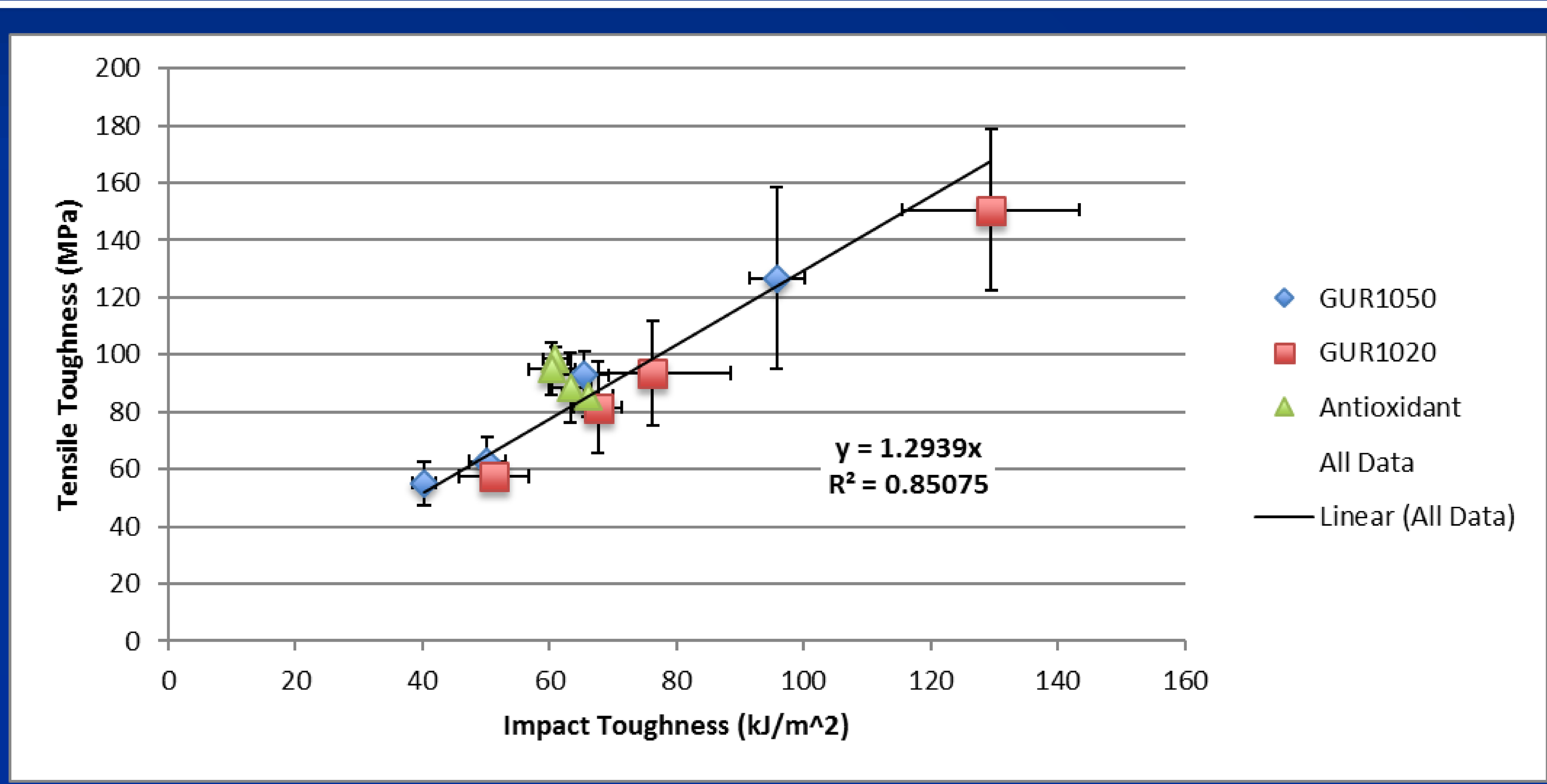

Figure 4: Tensile toughness vs. Impact Toughness

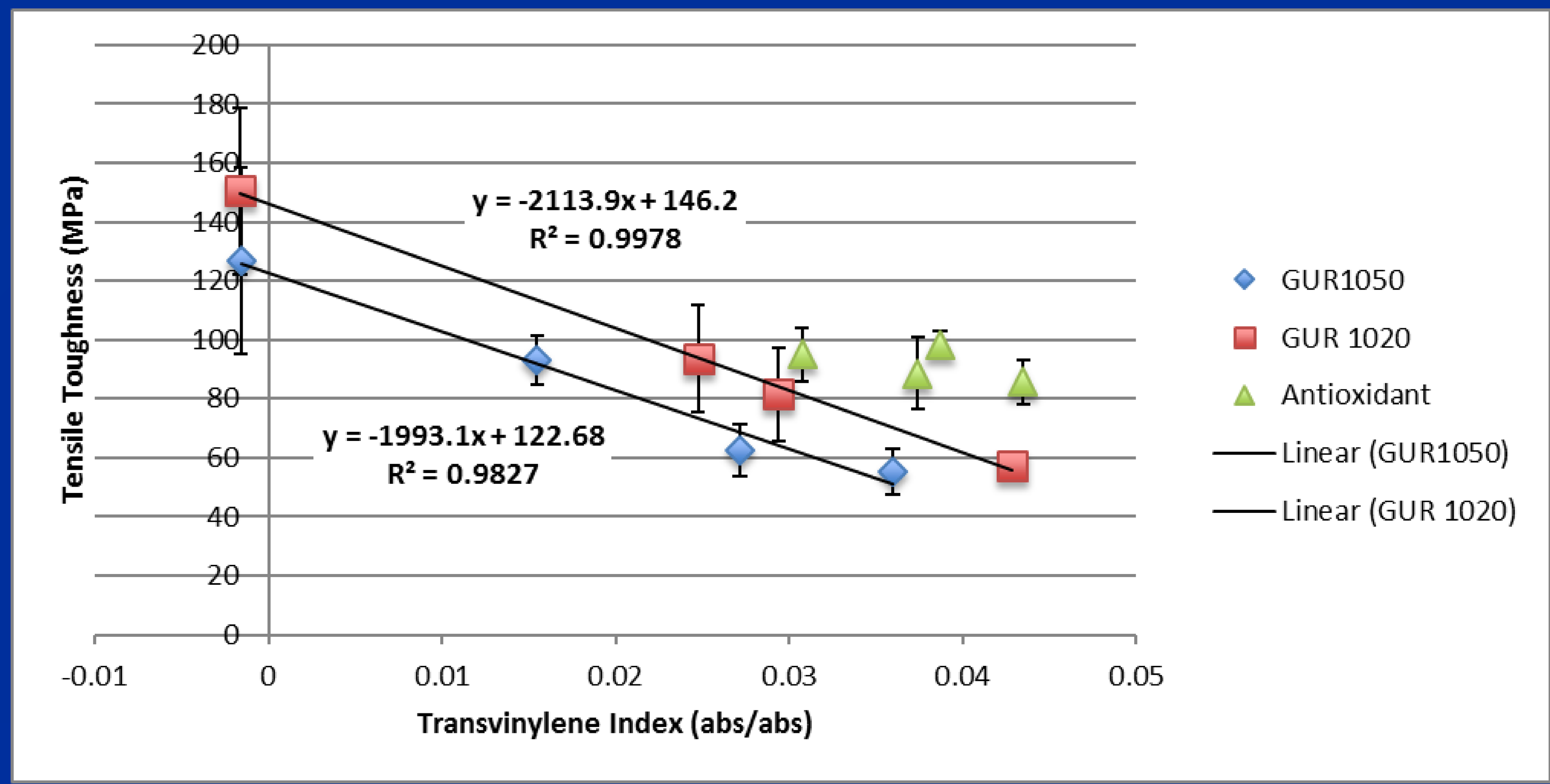

Figure 5: Tensile toughness vs. TVI

Results

- All materials followed one trendline (Figure 4), similar to the one found in the previous study considering only GUR 1020 UHMWPE
- Tensile toughness = 1.33 * Impact toughness
- Antioxidant and GUR 1050 UHMWPE had lower impact and tensile toughnesses than GUR 1020
- FTIR data showed no significant oxidation in the materials
- Both tensile and impact toughness decreased with increasing TVI for traditionally crosslinked, nonantioxidant materials, only tensile toughness vs. TVI shown above (Figure 5)

Discussion

Previous studies have demonstrated that higher radiation doses decrease the toughness of UHMWPE owing to the introduction of crosslinks and decreased ductility caused by reduced chain mobility[1]. This study used TVI in the place of nominal radiation dose to account for differences in cross-linking and sterilization methods, as the quality of absorbed radiation depends on source, environmental conditions, and thermal conditions. Overall, this work demonstrates that non-antioxidant materials followed the expected trend of decreasing toughness versus TVI, confirming earlier work that asserts resin type GUR 1020 is tougher than GUR 1050, and further asserting that the relationship between impact and tensile toughness is maintained in both types of materials[2]. The increased molecular weight of GUR 1050 explains its decreased toughness, due in part to reduced chain mobility and ductility. The results from the antioxidant materials are less conclusive, likely due in part to the small range of materials tested, both in terms of radiation doses, TVI, and toughness values in addition to the lack of uniformity of antioxidant treatments. Nonetheless, the results suggest that treating UHMWPE with antioxidants does not negatively affect its toughness, as evident from the GUR 1020. However, further work should be done, considering a wider range of radiation doses, and a more uniform antioxidant treatment, controlling for type of antioxidant added and the process by which it is added.

Significance/Clinical Relevance: This study extends previous work considering the influence of resin type on UHMWPE toughness and provides a start to further explore the affect or antioxidant additives to UHMWPE toughness.

References: (1) Huot, J. C., Van Citters, D. W., Currier, J. H. and Collier, J. P. (2011), The effect of radiation dose on the tensile and impact toughness of highly cross-linked and remelted ultrahigh-molecular weight polyethylenes. J. Biomed. Mater. Res., 97B: 327–333. doi:10.1002/jbm.b.31818
(2) Hunt, Benjamin J., Joyce, Thomas J. (2016), A tribological assessment of ultra high molecular weight polyethylene types GUR 1020 and GUR 1050 for orthopedic applications. Lubricants, 4. 25. doi: 10.3390/lubricants4030025