An Investigation on Crosslinking Uniformity in Irradiated UHMWPE

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Statement of Purpose: Radiation-induced crosslinking is responsible for wear improvement in UHMWPE implants, but it may cause reduction in mechanical properties, especially at high crosslinking density (CD). Gamma rays are adequate for sterilization due to its superior penetration, but distribution of crosslinks at both macro- and micro-structural levels deserves a close examination. Improvement in CD is expected to lead to better wear, toughness, and clinical performance. In this study, we purposely created a non-uniform radiation dose profile in a large UHMWPE rod followed by various post-radiation treatments to investigate the distribution of crosslinks.

Methods: A rectangular rod (8 cm x 10 cm x 28 cm) of GUR 1020 UHMWPE was irradiated in air by gamma rays in a setup where the rod was placed close to the source with its one end (front, 0 cm) facing toward while the other end (rear, 28 cm) away from the source. The received dose was 29 kGy at front and 9 kGy at rear as measured by dosimeters affixed at ends. Post-radiation annealing and re-melting treatments were done at 120 and 150°C for 4 hours. A third treatment was done at 240°C for 3 hours. Swell ratio profile was measured by immersing UHMWPE specimens in xylene at 130°C for 3 hours. All other steps followed ASTM D2765.

Results: Swell ratio and gel content data are presented in Table 1. Figures 1 through 4 show the swell ratio profiles. T-tests indicated that swell ratio values were significantly different among as-irradiated, annealed or re-melted, and 240°C treated (all $p < 0.03$), while there was no statistical difference between annealing and re-melting ($p = 0.40$).

Table 1: Swell ratio and gel content (%) profile

Pos	**As irrad.**		**Annealed**		**Re-melted**		**240°C**	
(cm)	Swell	Gel	Swell	Gel	Swell	Gel	Swell	Gel
0.3	4.80	89	3.57	87	4.03	90	3.09	100
0.6	3.89	97	3.28	100	3.15	100	2.91	100
0.8	4.02	98	3.28	100	2.98	100	3.08	100
1.0	4.08	97	3.25	100	3.22	100	2.93	100
5.0	4.19	94	3.43	100	2.95	100	3.34	100
10.0	5.14	96	3.88	100	3.97	100	3.01	100
15.0	5.31	90	3.70	100	3.87	100	3.51	100
20.0	5.95	95	4.28	100	3.87	100	3.01	100
25.0	6.42	95	4.44	100	4.47	100	3.13	97
28.0	6.92	92	4.98	98	5.92	97	3.27	100
Max /min	1.78	1.10	1.53	1.15	2.01	1.11	1.21	1.03
Ave.	5.07	94.3	3.81	98.5	3.84	98.7	3.13	99.7
STD	1.02	2.79	0.55	3.89	0.85	3.06	0.18	0.86

Discussion: Broad distribution of CD (in reverse relationship with swell ratio) was found in the as-irradiated material. Minimum of swell ratio, occurring at length of 0.6 cm, was 3.89 while maximum was 6.92 at the rear end which received the lowest dose. Average of swell ratio was 5.07. Annealing at 120°C lowered the average to 3.81, as it recombined free radicals further to form crosslinks. The wide spread of CD still existed, as indicated by large Max/Min (1.53) and standard deviation (0.55) values. Re-melting at 150*C showed similar results to annealing. All three materials (as-irradiated, annealed, and re-melted) exhibited a minimum of swell ratio at a location between 0.6 and 1.0 cm. Other studies on irradiated UHMWPE also reported a sub-surface maximum in radiation dose[1] or in oxidation[2] profile. Gel content was high except at ends. High temperature treatment at 240°C produced four major effects: (1) reducing the swell ratio spread to almost within experimental errors (Max/Min 1.21; standard dev. 0.18), (2) reducing the swell ratio average to 3.13 (lowest among the four), (3) exhibiting no sub-surface minimum, and (4) having high gel contents at ends. At 240°C, existing crosslinks were believed to be broken first and re-distributed uniformly. High temperature must have also broken chemical bonds (C-C or C-H bonds) for the formation of new free radicals and new crosslinks. Further studies will confirm the hypothesis.

Figure 1: Swell ratio profile/as-irradiated

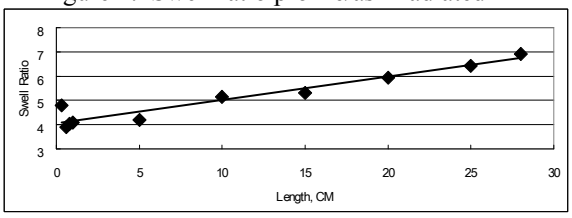


Figure 2: Swell ratio profile for annealed

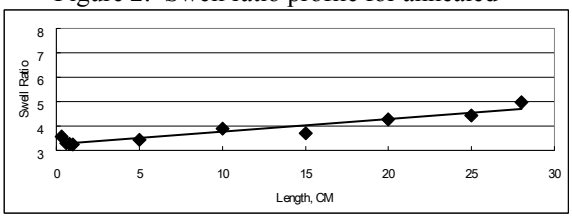


Figure 3: Swell ratio profile for re-melted

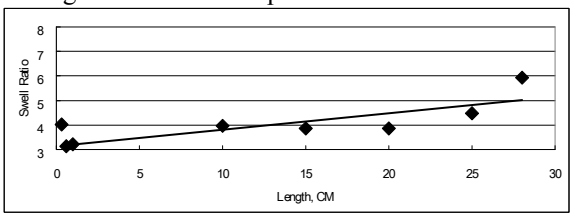
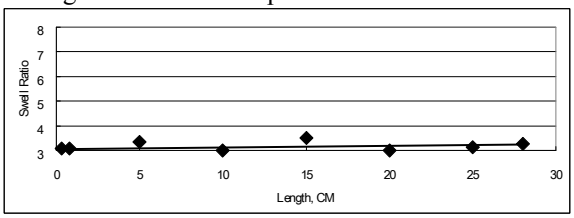


Figure 4: Swell ratio profile for 240*C treated



References:(1)V. Premnath, et al.,Biomaterials, 17, 1741-1753 (1996) (2) D.C. Sun, et al., 21th Annual Meeting of the Society For Biomaterials, P 362, 1995 **Acknowledgement:** Special thanks are given to Meditech Inc for providing UHMWPE material and Mr. ZH Chou at INER, Taiwan for radiation work.