Mechanical and oxidative performance of high-dose electron-beam irradiated, dl-α-tocopherol (vitamin E) blended UHMWPE

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Abstract
The mechanical and oxidative performance of dl-α-tocopherol (vitamin E, VE) blended Ultrahigh Molecular Weight Polyethylene (UHMWPE) exposed to varying levels of electron-beam radiation was evaluated using hip simulator testing, FT-IR spectroscopy, gel-fraction analysis, differential scanning calorimetry, and tensile testing. Gel fraction values for the irradiated samples increased with the radiation dose, but decreased with higher concentrations of vitamin E. However, for higher doses of electron-beam radiation, the effect of vitamin E concentration was reduced, and increased gel fraction values were observed. The gel fraction values and hip simulator wear resistance values for a 0.3% (w/w) vitamin E blended UHMWPE sample irradiated with 300 kGy were equal to that for commercially available, highly-crosslinked UHMWPE. In addition, no significant changes in oxidation index, crystallinity, tensile strength or elongation-at-break were observed for the 300 kGy irradiated, 0.3% (w/w) vitamin E blended UHMWPE following oxidative ageing (ASTM F2003). Losses in elongation-at-break values were observed for samples receiving increased radiation doses, with higher vitamin E concentrations helping to attenuate these losses. However, for samples receiving 300 kGy of radiation, even the 1.0% vitamin E blended sample experienced a significant loss in elongation-at-break compared with its non-irradiated counterparts.

Key words: Vitamin E blended ultrahigh molecular weight polyethylene, UHMWPE, Total hip replacement, Crosslinking

1. Introduction

Ultrahigh molecular weight polyethylene (UHMWPE) has been used in both Total Knee Replacement (TKR) and Total Hip Replacement (THR) for close to 50 years (Kurtz, 2009a; Kurtz, 2009b). However, there is substantial evidence that suggests that highly-crosslinked (XL) UHMWPE is more resistant to wear and may help prevent osteolysis and aseptic loosening, especially in THR. In both in vitro and clinical studies, XL-UHMWPE materials have demonstrated significantly improved wear resistance (Muratoglu, et al., 2001; Estok, et al., 2007; Kurtz, et al., 2011), suggesting that these materials can help reduce the total amount of wear debris produced over the lifetime of the implant. This, in turn, suggests that the material can help prevent the onset of wear-debris-induced aseptic loosening, which remains as a primary threat to implant longevity (Amstuz, et al., 1982; Jasty, 1993).

The improved wear resistance of these materials is derived directly from the high level of polyethylene chain crosslinking that is achieved following either gamma or electron-beam irradiation. However, this irradiative treatment also results in the creation of unrequited polyethylene radicals that, in the presence of oxygen, can initiate an oxidation cascade that can eventually lead to the deterioration of the material’s mechanical properties (Costa, et al., 1998; Costa and...
Bracco, 2009). dl-α-Tocopherol (vitamin E), which is a natural anti-oxidant, has been previously used in non-crosslinked UHMWPE (Tomita, et al., 1999; Wolf, et al., 2002), with various studies showing it to be an effective additive for protecting the material from oxidative degradation (Teramura, et al., 2004; Kurtz, et al., 2009; Teramura, et al., 2009; Rowell, et al., 2011). As a result, attempts have been made to introduce dl-α-Tocopherol (vitamin E) to XL-UHMWPE to ensure the material’s long term oxidative stability (Parth, et al., 2002; Oral, et al. 2005; Oral, et al., 2008; Oral, et al., 2010; Oral, et al., 2004; Oral, et al., 2007; Oral and Muratoglu, 2011).

However, due to its natural radical scavenging capabilities, incorporating vitamin E into UHMWPE prior to crosslinking has been shown to limit the degree to which the material can be crosslinked. In various studies, increasing concentrations of vitamin E in the pre-irradiated material have corresponded with decreasing crosslink densities in the final material (Parth, et al., 2002; Oral, et al. 2005; Oral, et al., 2008; Oral, et al., 2010). In other studies, introducing vitamin E into UHMWPE after crosslinking has been shown to be an effective method for realizing a vitamin E containing, highly-crosslinked UHMWPE material (Oral, et al., 2004; Oral, et al., 2007). These attempts have been successful primarily in achieving elevated concentrations of vitamin E at the surface of the material, with further post-processing required for creating a more uniform distribution of vitamin E within the material.

In this study, vitamin E was added to the UHMWPE resin mixture prior to material formation, and the effects of vitamin E blending and electron-beam radiation were examined in an attempt to create a highly-crosslinked, vitamin E blended UHMPWE suitable for THR. Hip simulator testing, FT-IR spectroscopy, gel-fraction analysis, differential scanning calorimetry, and tensile testing were used to evaluate the tribological and mechanical performance of the different materials. Compulsory oxidative ageing was also performed to investigate the oxidative stability of the samples following irradiation.

2. Materials and methods

2.1. Materials

Virgin and vitamin E blended UHMWPE resin mixtures were created by combining GUR 1050 UHMWPE resin powder (Ticona Inc., USA) with vitamin E (dl-α-tocopherol, Eisai Co. Ltd., Japan) at concentrations of 0 (virgin), 0.1, 0.3, and 1.0% (w/w) prior to formation. Samples were then produced through direct compression molding at 220°C and 25 MPa. Crosslinked samples were created by irradiating at 30, 90, or 300 kGy with a 10MeV electron beam at room temperature in vacuumed sealed packaging. Crosslinked samples were subsequently annealed by placing them in a 110°C environment for 72 hours.

Gamma irradiated (95 kGy), highly-crosslinked GUR 1020 UHMWPE samples were purchased from Quadrant Plastics Composites (Mie, Japan) and used as a control for wear measurement in hip simulator testing. As purchased, the samples had been annealed for 72 hours at 110°C. To avoid confusion, electron-beam irradiated samples were denoted by GUR XXXkGy, where XXX represents the radiation dose in kGy, while the gamma irradiated controls samples were denoted GUR XL. Ageing for both virgin and vitamin E blended samples was done in accordance with ASTM standard F2003, while no samples were sterilized.

It must be noted that molecular weight of the GUR XL control material and that for the GUR XXXkGy experimental materials was different, with the the control material produced from a GUR-1020 resin (MW = 3.5 × 10⁶ g/mol) and the experimental samples made from a GUR-1050 resin (MW = 5.5-6 × 10⁶ g/mol) (Kurtz, et al., 1999).

2.2. Crystallinity, gel fraction, and oxidation index

As a measure of the materials crosslink density, gel fraction measurements were performed for the different materials (Spiegelberg, 2009). Gel fraction samples (weight = 5 g, N = 3) were weighed and then soaked in decalhydroneaphthlene (Sigma Aldrich) at 150°C for twelve days using a meshed cage with 200 μm pores. Residual decalhydroneaphthlene was then removed using a soxhlet extractor with hexane (Nacalai Tesque, Japan) at 100°C for 24 hours. Samples were then dried and weighed, with the difference in weight used to calculate the amount of non-crosslinked material.

Oxidation Index (OI) was determined in accordance with ASTM F2102 with an FT-IR spectrometer (Spectrum 100 equipped with Spot light 200, Perkin Elmer). The ratio of the carbonyl peak (1680 to1760cm⁻¹) to the methyl- and methylene-peaks (1320 to 1390cm⁻¹) was measured for samples (N = 3) both before and after compulsory ageing. Crystallinity was measured via differential scanning calorimetry (DSC), where 1.0±0.05 mg samples (N = 3) were heated and the resulting enthalpy curve was integrated from 80 to 150°C and normalized with respect to that for a 100% crystalline polyethylene (291J/g) sample. Samples for both OI and DSC measurement were cut from the ends of the tensile testing specimens.

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2.3. Tensile testing

A tensile testing system (Model 5965, Instron) was used to measure the yield strength and elongation-at-break for the different samples. Direct compression molded dog-bone tensile specimens (thickness = 3 mm, N = 5) were evaluated using a cross head speed of 50 mm/min in accordance with JIS K7113. Tests were performed both before and after compulsory ageing.

2.4. Hip simulator testing

The wear performance of the Virgin (GUR), XL (GUR XL), and 0.3% (wt/wt) vitamin E blended UHMWPE (GUR VE) samples were tested in a twelve station hip simulator (AMTI-Boston, VA, USA) both before and after compulsory ageing. Dome samples (shown in Fig. 1) were direct compression molded and then machined to create the liners (N = 3). The inner diameter of the liners was 26 mm and the thickness of the sample liners was 10 mm. For all hip simulator experiments, the motion and loading of the implants were implemented according to ISO14242-1. (A description of the ISO loading conditions can also be found in Wimmer and Laurent, 2011.) A Co-Cr-Mo (ASTM F799) femoral head with a 26 mm diameter was used, and all tests were conducted at a frequency of 1 Hz for one million cycles using a lubricant composed of 25% bovine calf serum, 0.3% sodium azide, and ultra-pure water. The resulting gravimetric wear was measured after the first 0.5 million cycles and every million cycles thereafter by calculating the difference in mass of the specimens before and after testing, and then converting to volumetric wear using the known densities of the sample materials. The before and after weight of unloaded specimens placed in the same lubricant were also measured to control for water, lipid, and protein adsorption during testing.

Fig. 1: Dimensions of the liner used in the hip simulator experiments.

2.5. Statistical analysis

Statistical analysis for all tests was performed using a two-tailed Student’s t test. Statistical analysis was performed between all samples for each test. However, only for groups sharing at least one variable (vitamin E concentration or radiation dose) were statistically significant differences labeled.

3. Results

3.1. Crystallinity, gel fraction, and oxidation index

Figure 2 shows the gel fraction results for virgin and 0.1, 0.3, and 1.0% (wt/wt) vitamin E blended UHMWPE samples before (0kGy) and after (30, 90, 300 kGy) radiation. As can be seen in the figure, the gel fraction for each sample increases with increasing radiation dose. Additionally, among samples with the same radiation dose, higher concentrations of vitamin E corresponded with lower gel fraction values.
Fig. 2: Gel fraction results for the 0, 0.1, 0.3, and 1.0% vitamin E blended UHMWPE samples irradiated at 0, 30, 90, and 300 kGy. Symbols a, b, and c represent a statistical difference between the labeled sample and the respective 300, 90, and 30 kGy irradiated samples of the same vitamin E concentration (p ≤ 0.01). The symbol * signifies a statistical difference between the marked samples (p ≤ 0.01).

The oxidation index (OI) measurements for virgin and 0.3% (wt/wt) vitamin E blended UHMWPE samples irradiated at 300 kGy (both before and after ageing) are shown in Fig. 3. For the non-aged samples, no differences in OI value were observed between the virgin and vitamin E blended UHMWPE materials. However, after ageing, the virgin UHMWPE samples displayed significantly higher OI values at the surface of the specimens that decreased with sample depth. In contrast, no changes in the OI values were observed between the non-aged and aged vitamin E blended UHMWPE samples.
Fig. 3: Oxidation index (OI) values for the aged and no-aged virgin UHMWPE samples irradiated at 300 kGy (A) and the aged and non-aged 0.3% vitamin E blended UHMWPE samples irradiated at 300 kGy (B). The * symbol signifies a significant difference between the aged and non-aged samples at the marked sample depth (p ≤ 0.05).

Crystallinity values for the virgin, and 0.1, 0.3, and 1.0% (wt/wt) vitamin E blended UHMWPE samples irradiated at 0, 30, 90, and 300 kGy are shown in Fig. 4A (before ageing) and 4B (after ageing). For all non-aged samples (both virgin and vitamin E blended), crystallinity values were slightly higher for samples that received higher doses of radiation. For the aged samples, the crystallinity values for the vitamin E blended samples were again higher for higher radiation doses. However, for the virgin samples, the opposite trend was observed; for samples with higher doses of radiation, crystallinity decreased. Looking at the aged and non-aged samples, there was no observed change between the respective vitamin E blended samples. However, for the 0, 30, and 90 kGy irradiated virgin samples, there was a significant increase in crystallinity for the aged samples compared to the non-aged samples, with this change attenuated at higher radiation doses.
**Fig. 4:** Crystallinity values for the 0, 0.1, 0.3, and 1.0% vitamin E blended UHMWPE samples irradiated at 0, 30, 90, and 300 kGy before (A) and after (B) accelerated ageing. Symbols a, b, and c represent a statistical difference between the labeled sample and the respective 300, 90, and 30 kGy irradiated samples of the same vitamin E concentration ($p \leq 0.01$). The symbol * signifies a statistical difference between the marked samples ($p \leq 0.01$). The symbol z denotes a significant difference between the labeled aged and non-aged samples of the same vitamin E concentration and radiation dose ($p \leq 0.01$).

### 3.2. Tensile testing

As can be seen in Fig. 5A, there were no significant changes in the yield strength between the non-aged materials, with neither vitamin E concentration nor radiation dose exhibiting an influence on the results. For the aged samples (shown in 5B), the average yield strength values for the virgin samples were slightly lower than their respective non-aged counterparts, although these changes were not found to be significant.
The elongation-at-break results are shown in Fig. 6. For the non-aged samples, increasing radiation corresponded with decreasing elongation-at-break values. As can be seen, for all concentrations of vitamin E, the samples irradiated at 300 kGy exhibited the lowest elongation-at-break values. Also, increasing elongation-at-break values were observed for samples with higher concentrations of vitamin E. However, the only statistically significant increase observed between samples that received the same radiation dose was found between the virgin and 1.0% vitamin E blended samples irradiated at 90 kGy. As can be seen in Fig. 6B, there were no observed changes between the non-aged and aged vitamin E blended samples. However, for the virgin samples, significant reductions in elongation-at-break value were observed between the non-aged and aged samples.
3.3. Hip simulator testing

The hip simulator results for the virgin (GUR), vitamin E blended (GUR VE), and highly crosslinked UHMWPE (GUR XL) samples are shown in Fig. 7. As can be seen, both virgin and vitamin E blended UHMWPE produced essentially the same amount of wear debris both before and after compulsory ageing. In contrast, a 50% decrease in the total volume of wear produced was observed for the virgin and vitamin E blended UHMWPE samples following oxidative ageing. For both the aged and non-aged samples, the highly crosslinked UHMWPE samples (XL UHMWPE) produced significantly less wear compared with either the virgin and vitamin E blended UHMWPE samples.

Fig. 6: Elongation at break values for the 0, 0.1, 0.3, and 1.0% vitamin E blended UHMWPE samples irradiated at 0, 30, 90, and 300 kGy before (A) and after (B) compulsory ageing. Symbols a, b, and c represent a statistical difference between the labeled sample and the respective 300, 90, and 30 kGy irradiated sample of the same vitamin E concentration (p ≤ 0.01). The symbol * signifies a statistical difference between the marked samples (p ≤ 0.01). The symbol z denotes a significant difference between the labeled aged and non-aged samples of the same vitamin E concentration and radiation dose (p ≤ 0.01).
Fig. 7: Volumetric wear results from hip simulator testing for the virgin, 0.3% vitamin E blended, and highly crosslinked UHMWPE samples before (A) and after (B) compulsory ageing. Symbols a and b represent a significant difference between the highly crosslinked UHMWPE samples and the respective virgin and VE blended samples for the labeled number of cycles ($p \leq 0.01$). The symbol c signifies a significant difference between the virgin and VE blended UHMWPE samples for the labeled number of cycles ($p \leq 0.01$). The symbols u, v, w denote a significant difference between the non-aged and aged samples for the respective virgin, VE blended, and highly-crosslinked materials at the labeled number of cycles ($p \leq 0.01$).

The results for the 0.3% (w/w) vitamin E blended UHMWPE samples that were irradiated at 30, 90, or 300 kGy are shown in Fig. 8. As can be seen, there was an inverse relationship between radiation dose and wear volume; as the radiation dose was raised from 30 to 90, and finally to 300 kGy, the measured wear volume decreased significantly (significance not shown). There was a slight increase in wear resistance observed between the unirradiated and 30 kGy irradiated vitamin E blended samples. With a radiation dose of 90 kGy, the final wear volume was roughly four times less than that for the unirradiated, vitamin E blended UHMWPE. Increasing the radiation dose to 300 kGy resulted in a further reduction in wear volume, achieving a wear resistance that was almost identical to that for the gamma irradiated, highly...
The goal of this study was to investigate the effect of vitamin E blend concentration and elevated levels of electron-beam radiation on gel fraction and mechanical performance, including hip-simulator wear resistance testing, for vitamin E blended UHMWPE. Parth et al. previously found that for low doses of crosslinking radiation (≤25 kGy), increasing vitamin E concentration (0.2, 0.4, and 0.8% w/w) resulted in reduced gel fraction values (Parth, et al., 2002). By increasing the radiation dose to 100 kGy, Parth et al. observed diminished reductions in gel fraction value within the vitamin E blended samples relative to the unblended, virgin control. However, the gel fraction values for these vitamin E blended samples remained below that for the virgin sample. Similarly, Oral et al. measured the crosslink density and wear resistance of 0 (virgin), 0.1 and 0.3% (w/w) vitamin E blended UHMWPE samples crosslinked with a radiation dose of 100 kGy (Oral, et al. 2005). Again, vitamin E concentration dependent decreases in both crosslink density and wear

4. Discussion

The goal of this study was to investigate the effect of vitamin E blend concentration and elevated levels of electron-beam radiation on gel fraction and mechanical performance, including hip-simulator wear resistance testing, for vitamin E blended UHMWPE. Parth et al. previously found that for low doses of crosslinking radiation (≤25 kGy), increasing vitamin E concentration (0.2, 0.4, and 0.8% w/w) resulted in reduced gel fraction values (Parth, et al., 2002). By increasing the radiation dose to 100 kGy, Parth et al. observed diminished reductions in gel fraction value within the vitamin E blended samples relative to the unblended, virgin control. However, the gel fraction values for these vitamin E blended samples remained below that for the virgin sample. Similarly, Oral et al. measured the crosslink density and wear resistance of 0 (virgin), 0.1 and 0.3% (w/w) vitamin E blended UHMWPE samples crosslinked with a radiation dose of 100 kGy (Oral, et al. 2005). Again, vitamin E concentration dependent decreases in both crosslink density and wear
resistance were observed. Oral et al. further investigated the relationship between crosslinking radiation and vitamin E concentration by examining the effects of higher dose radiation (100, 150, and 200 kGy) on 0 (virgin), 0.1, 0.3, and 1.0% (w/w) vitamin E blended UHMWPE samples (Oral, et al., 2008). Vitamin E concentration dependent reductions in crosslink density were also observed for samples receiving the same radiation dose. However, the crosslink density values for the 0.1% vitamin E blended samples irradiated at 150 and 200 kGy were found to equal or exceed the crosslink density value for the 100 kGy irradiated virgin sample.

In the current study, vitamin E concentration dependent relationships in both gel fraction and wear resistance were observed, with increasing vitamin E concentration found to reduce both gel fraction and wear resistance for samples experiencing the same level of radiation. The gel fraction values for the 90 kGy irradiated 0.1% vitamin E sample and the 300 kGy irradiated 0.3% vitamin E blended samples, however, were substantially equivalent to the virgin sample irradiated at 90 kGy. Although less reliable than crosslink density in predicting wear resistance (Spiegelberg, 2009), these gel fraction results suggest for these specific vitamin E concentrations and radiation doses that is possible to create a highly-crosslinked, vitamin E blended UHMWPE material. This is supported by the hip-simulator wear resistance results, where there was no difference in observed wear volume at each measurement point for the highly-crosslinked, virgin control sample and the 300 kGy irradiated, 0.3% vitamin E blended UHMWPE sample.

Taken in combination with the results of the studies mentioned above, the results of this study provide further evidence that vitamin E in the pre-irradiated material inhibits crosslinking for low levels of radiation. However, the current results, along with those from the work of Oral et al., suggest that for concentrations of vitamin E below 0.3% (w/w), higher doses of radiation (≥150 kGy) can be used to reduce the limiting effect of vitamin E on crosslinking. For vitamin E concentrations above 0.3% (w/w), it is possible that further increases in radiation dose (>300 kGy) may be able to achieve similar increases in crosslinking. However, further work is necessary to investigate this hypothesis.

The secondary goal of this study was to investigate how these increases in radiation might alter the oxidative and mechanical stability of vitamin E blended UHMWPE. Previous studies have investigated the effects of radiation and oxidative ageing on vitamin E blended UHMWPE, but the effects of radiation above 150 kGy have not yet been clarified. In an investigation by Kurtz et al., it was found that vitamin E concentrations as low as 0.0125% (w/w) were able to prevent oxidation following accelerated ageing for gamma irradiated (75 kGy in air) samples. In another study, Oral et al. observed no oxidation in 100 kGy irradiated, 0.1 and 0.3% (w/w) vitamin E blended samples following oxidative ageing (Oral, et al., 2008). Fu et al. were also unable to detect oxidation in 0.1 and 0.2% vitamin E blended UHMWPE materials exposed to 150 kGy of electron-beam radiation following oxidative ageing (Fu, et al., 2013).

In this investigation, significant increases in oxidation index measured at the surface of the 300 kGy irradiated, virgin samples were observed following compulsory ageing. In contrast, no detectable changes in oxidation index were observed for the 300 kGy irradiated, 0.3% vitamin E blended samples after ageing. Significant increases in crystallinity were also observed following ageing for the 0, 30, and 90 kGy irradiated, virgin samples, suggesting the occurrence of recrystallization at sites of oxidation-induced chain scission (Bhatjea, et al., 1982). Similarly, significant decreases in elongation-at-break were observed for the virgin samples for all radiation doses following compulsory ageing, while no statistical differences were observed for any of the vitamin E blended samples before and after ageing. Decreases in yield strength were also observed for the 0, 30, and 90 kGy irradiated virgin samples before and after ageing, but these changes were not found to be significant.

These results suggest that while both oxidation and oxidative degradation occurred in the virgin samples, the presence of vitamin E helped to prevent either from occurring in the vitamin E blended samples. Additionally, in combination with the confirmation of vitamin E radicals within irradiated vitamin E blended UHMWPE (Turner, et al., 2014), these results further support the hypothesis that vitamin E radicals are able to suppress the oxidation cycle within UHMWPE (Bracco, et al., 2007). Although oxidation index measurements were not made for the 300 kGy irradiated, 0.1% vitamin E blended samples, the elongation-at-break results for this material also support the thesis of Kurtz et al., which states that relatively low concentrations of vitamin E are sufficient to prevent oxidation in UHMWPE. In fact, further optimization work might be able to identify a more precise relationship between the necessary amount of vitamin E necessary to prevent oxidation for a given radiation dose.

However, significant reductions in elongation-at-break were observed for all samples, both virgin and VE blended, that were irradiated at 300 kGy. So while vitamin E was able to prevent further reductions in elongation-at-break resulting from oxidative degradation, vitamin E was not able to prevent losses in elongation-at-break as a result of high dose irradiation. This is most likely the direct result of the increased crosslinking that was observed for these samples, as other studies have demonstrated a general inverse relationship between the two properties (Khonakdar, et al., 2003, Dadbin, et
An issue that this investigation fails to address how vitamin E concentration and radiation dose affect the biological activity of vitamin E blended UHMWPE. In a previous study, it was found that vitamin E blended wear particles induced a reduced biological response relative to virgin wear particles when cultivated with human white blood cells (Bladen, et al., 2013). Initial results suggested that this was a direct result of vitamin E, but this has not been confirmed. It is possible that higher levels of radiation and the conversion of vitamin E to vitamin E radicals or other oxidative products may influence this biological phenomenon. Therefore, in future work it will be necessary to investigate if the high doses of radiation used in this study alter the previously observed biological activity of vitamin E blended UHMWPE.

Additionally, further investigation is required for the hip simulator wear results for the aged virgin UHMWPE and aged VE blended UHMWPE samples. In this study, ageing of the virgin and VE blended samples resulted in a significant decrease in hip simulator wear for both samples. It is possible that the elevated temperatures used during the oxidative ageing process may have caused a change in the microstructure of the two materials at the surface of the implant samples. For future work, it would be instructive to investigate possible changes in crystallinity, micro-hardness, and gel fraction at the surface of the different materials. Additionally, further tribological testing, including a repeat of the hip simulator tests performed in this study, would be necessary to fully investigate this matter.

5. Conclusion

Through mechanical and oxidative evaluation, a combination of 0.3% (w/w) vitamin E in the UHMWPE resin mixture with an radiation dose of 300 kGy following material formation was suggested for creating a highly-crosslinked, vitamin E blended UHMWPE material. This material exhibited the same wear resistance as gamma irradiated, highly-crosslinked, virgin UHMWPE, while oxidation and mechanical testing results revealed that no oxidation nor oxidative degradation occurred during compulsory oxidative ageing. This suggests that following radiation, vitamin E or vitamin E radical products within the blended material are still able to act as oxidative stabilizers and prevent oxidation within the material. However, as a probable result of the increased crosslinking, a significant decrease in elongation-at-break was observed for the 0.3% (w/w) vitamin E blended sample irradiated at 300 kGy relative to other 0.3% (w/w) vitamin E blended samples that received lower amounts of radiation.

Further testing is required to investigate whether such levels of radiation affect the materials biological properties (Bladen, et al., 2013). Specifically, it is necessary to investigate the generation of vitamin E radicals during radiation, and to examine whether the generation of these radicals or subsequent chemical products will affect the previously observed biological activity of non-irradiated, vitamin E blended UHMWPE.

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