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Effect of Electron Beam Irradiation on Load-displacement Responses of UHMWPE

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Ultra-High Molecular Weight Polyethylene (UHMWPE) has been used successfully for articulating surfaces of joint endoprostheses, *i.e. cup linear on acetabular component of total hip arthroplasty*, in orthopaedics for over three decades. Although numerous attempts have been performed to characterize and to improve the polymeric material, *i.e. to reduce the molecular degradation due to in vivo oxidation*, the effect of electron beam irradiation on load-displacement characteristics of UHMWPE has not been reported clearly. The aim of the current study is to quantify the effect of the electron beam irradiation with alteration of the amount of irradiation on the mechanical characteristics of the polymeric material. In this work, monotonic uniaxial and small punch tests were conducted to examine the relative capabilities of four samples irradiated with electron beam at 0, 50, 100, and 150 kGy, based on a prediction of mechanical behavior of the UHMWPE materials. Load-displacement behaviors of UHMWPE were not changed significantly by electron beam irradiation less than 150 kGy although the stiffness of irradiated UHMWPE decreased gradually. Conclusively, changes of stiffness and deflection by irradiation were not significant. However, load characteristics were significantly changed by irradiation.

Key words: UHMWPE, Electron beam irradiation, Mechanical characteristics

Introduction

Ultra-High Molecular Weight Polyethylene (UHMWPE) is the material of choice for one of the articulating surfaces in total joint replacements. However, the problem of wear particle production causes a need for further investigation of this important biomaterial.[1)] Wear of UHMWPE is a major factor affecting the longevity of total joint arthroplasty because debris from the wear of polyethylene can elicit biological responses and cause periprosthetic osteolysis, which leads to loosening of the prostheses.

Ediding *et al*.[2)] and Mckellop *et al*.[3)] showed exponential decreases in wear with increased irradiation dose. Degradation of UHMWPE following gamma sterilization in air has been also associated with decreased longevity of some total artificial joints.[4,5)] Kurtz *et al*.[4] have studied the physical and chemical properties of UHMWPE following gamma sterilization extensively after natural and accelerated aging.

The effect of electron beam irradiation on UHMWPE mechanical behavior as derived from tests on clinically relevant hip or knee components has not been well documented, mainly due to the difficulty with using conventional, relatively large mechanical test specimens for such characterization. The development and validation of miniature specimen testing techniques, such as the small punch test, now permits direct measurement of UHMWPE mechanical properties as a function of electron beam irradiation in clinically relevant components.

In this work, we have used monotonic uniaxial and small punch tests to examine the relative capabilities of four samples irradiated with electron beam at 0, 50, 100, and 150 kGy, based on a prediction of mechanical behavior of the UHMWPE materials.

Materials and Method

Disk-shaped small punch specimens, measuring 6.4 mm in

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diameter and 0.5 mm in thickness, were machined from an extruded UHMWPE rod of GUR1020 (Quadrant PHS Deutschalnd GmbH) according to ISO 5834[6] and ASTM(American Society for Testing and Materials) F648.[7] Small punch specimens were carefully machined from the stock material to avoid phase changes near the surface.

Specimens were classified into four groups according to capacity of electron beam irradiation (Control: 0 kGy; n=5, Comparison 1: 50 kGy; n=6, Comparison 2: 100 kGy; n=6, Comparison 3: 150 kGy; n=6). The electron beam radiation was performed at medium energy electron accelerator (ELV-8, EB tech, Daejeon, Korea) and the energy range of which was from 1.0MeV up to 2.5MeV (Figure 1). The degree of electron beam irradiation absorption per 1 time was 25 kGy. The absorbed dosage (0-150 kGy) was determined photometrically according to the plan in controlling amount of irradiation defined in this study.

Mechanical testing was performed in bending by indentation of the disk-shaped polyethylene specimens with a custom-built, hemispherical head steel punch as described in previous studies,[8,9] based on a procedure suggested by ASTM F2183-02[10] (Figure 2(a)). Specimens were placed within an assembled coin-shaped holder before indentation with the hemispherical head punch (Figure 2(b)). The specimen guide, die, and punch were mounted within a testing frame of Instron micro-test system (5848 series, Instron, Norwood, MA, USA). The parts of small punch test apparatus were fabricated from hardened steel. The specimen was loaded by the hemispherical head punch moving into the specimen at a constant punch displacement rate of 0.5 mm min^{-1} until a failure of the specimen occurred. During the testing the punch load and displacement were digitally recorded from a 1 kN capacity load cell and an extensometer, respectively.

Statistical analyses were performed using statistical package for the social sciences (SPSS 12.0, SPSS Inc., USA). Standard analysis of variance techniques (ANOVA) test with *Tukey's-b post hoc multiple comparisons* was used to identify significant difference among the four groups. Here, the significance level was set at 0.05.

Results and Discussion

The current study quantified the effect of the electron beam irradiation with alteration of the amount of irradiation on the mechanical characteristics of the polymeric material. In this paper, miniature specimens were employed because an alternative miniature specimen technique, the small punch test, is necessary to fully characterize the spatially and temporally varying properties in polyethylene components after manufacture, sterilization, shelf aging, and implantation. The test

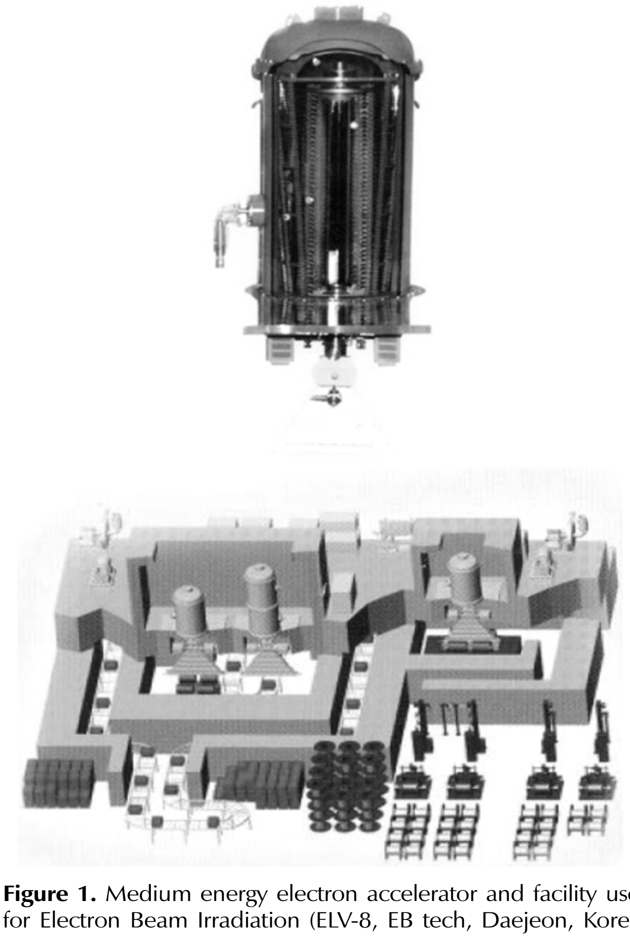

Figure 1. Medium energy electron accelerator and facility used for Electron Beam Irradiation (ELV-8, EB tech, Daejeon, Korea).

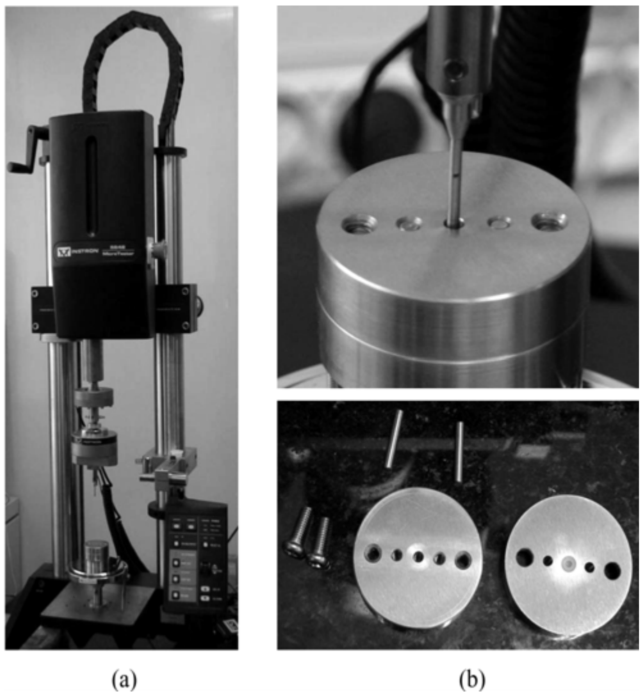

Figure 2. Small punch test apparatus. (a) Instron micro-test system (5848 series, Instron, Norwood, MA, USA), (b) Testing guide, die and hemispherical head punch.

method for this research was followed ASTM F2183-02. There are several kinds of test methods to evaluate the compressive characteristics. However, indentation test is very precise evaluation method especially for small specimens such as tissue of human or animal. In this context, indentation was employed for this research. Dosage of electron-beam was ranged from 0 Gy to 150 Gy for this research in order to characterize the variation of UHMWPE properties according to irradiation. Another reason for dosage is that dosage of electron-beam for medical device sterilization is not fixed but dependent on case.

The capabilities of the hybrid model to predict the mechanical behavior of UHMWPE can be seen from a direct comparison between the experimental data. The representative load–displacement behavior of UHMWPE small punch test specimens displayed similar distinctive features regardless of the amount of the electron beam irradiation (Figure 3). Load-displacement responses, followed by all very repeatable results in each group, showed that individual peak load at yield points occurred at the different quantity of applied electron beam irradiation. The effect of irradiation to UHMWPE on load characteristics could be intuited. The peak load of a control group (0 kGy) in uniaxial bending was higher than that of comparison groups (50-150 kGy), and lowly electron beam irradiated models had higher values of peak load than highly electron beam irradiated models had for this small punch test.

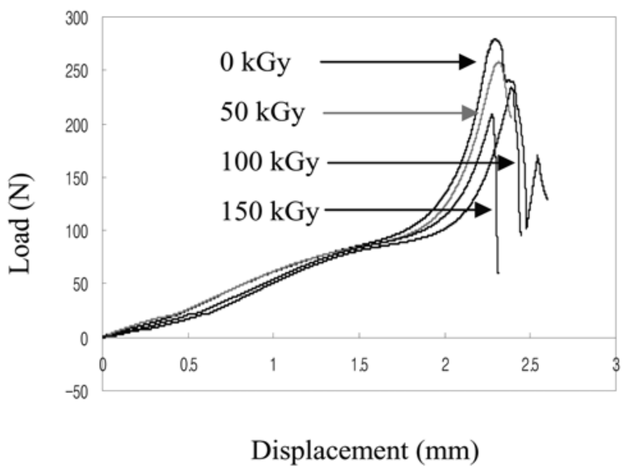

Figure 3. Representative load-deflection curves.

Table 1. Load at yield point, Deflection at yield point and Stiffness of UHMWPE small punch test specimens.

	Load(N) at yield point	Deflection(mm) at yield point	Stiffness(N/mm)
0 kGy	280.0	2.3	83.3
50 kGy	254.8±20.4	2.4±0.1	73.7±3.6
100 kGy	236.4±15.5	2.3±0.1	72.3±5.4
150 kGy	227.0±19.1	2.2±0.1	73.4±5.0

Stiffness, deflection, load properties of electron beam irradiated specimens were calculated from the load-displacement experiment and summarized in Table 1. The changes of stiffness and deflection by irradiation were not significant. However, load characteristics were significantly changed by irradiation.

The small punch test was a reproducible miniature specimen testing technique which could be used to characterize the work to brittleness and ductility of UHMWPE used in total joint replacements. The results of the current study demonstrated that the load displacement curve was insensitive to the effect of electron beam irradiation in the test samples and only mildly sensitive. Although there were statistically no significant differences among mechanical behaviors of the four groups, the average values of the stiffness were gradually decreased by electron beam irradiation.

Any process or material change proposed for polyethylene can be screened using a small punch test capable of detecting local differences in material properties at the articulating surface. From the mechanical point of view, it may indicate that the electron beam irradiation does not affect the mechanical behaviors of the UHMWPE.

Conclusion

Monotonic uniaxial and small punch tests were conducted to examine the relative capabilities of four samples irradiated with electron beam at 0, 50, 100, and 150 kGy, based on a prediction of mechanical behavior of the UHMWPE materials. The changes of stiffness and deflection by irradiation were not significant. However, load characteristics were significantly changed by irradiation.

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