The gamma crosslinking of polyethylene prostheses – some technical perspectives

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Abstract

The two major radiation crosslinking techniques developed for ultra-high molecular weight polyethylene (UHMWPE) prostheses and the ensuing clinical implications thereof are discussed, indicating the effects of the different techniques on clinical outcomes.

Key words: crosslinking, polyethylene, UHMWPE, prostheses

Introduction

The radiation crosslinking of ultra-high molecular weight polyethylene (UHMWPE) to enhance the properties of implants made from this polymer was reported as early as 1974 by Dumbleton.[1] These studies were carried out at very high irradiation doses in air or nitrogen and resulted in excessive surface oxidation of the polymer and poor wear characteristics. The general radiation crosslinking of UHMWPE in the presence of gaseous mediating agents to enhance the mechanical properties of the polymer was reported as early as 1972 by Mitsui[2] and in 1973 by Hagiwara.[3]

In order to reduce the required irradiation dose, authors 1 and 2 (Du Plessis and Grobbelaar) initiated a research and development programme in 1974 to investigate the potential of the radiation crosslinking of UHMWPE for application in orthopaedic prostheses by using a mediating gas or mixtures of mediating gases to enhance the degree of crosslinking of the UHMWPE and lower the required radiation dose. Almost 25 years later the first reports on the radiation crosslinking of UHMWPE prostheses in Europe and the USA started appearing. In these studies an inherently different radiation *crosslinking technique* was developed compared to the technique developed in the mid-seventies in South Africa.[4-6] Although the two crosslinking techniques are completely different and render different results, little appreciation still exists in general, as well as in assessing the two techniques. This situation led to the filing of the trademark Gammalink® in South Africa in order to uniquely distinguish the *technique* developed in South Africa from those developed in mainly the USA. This technical note serves the purpose to clearly distinguish the different radiation crosslinking techniques used today in enhancing the properties of UHMWPE prostheses and their clinical implications.

Historical development of the techniques

The development of the Gammalink® technique was initiated in 1974 by two senior orthopaedic surgeons and a radiation polymer chemist at the South African Atomic Energy Board. Following the initial extensive laboratory assessment of the technique, clinical applications were introduced in 1976. The first public report on the technique was presented in 1978 at the First International Meeting on Radiation Processing in Puerto Rico and subsequently published in 1978.[4-6] The preliminary clinical report pertaining to these clinical trials was the first ever to be reported in the literature on radiation crosslinked UHMWPE hip implants in the orthopaedic world literature.[5]

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With regard to the USA developments on the radiation crosslinking of UHMWPE prostheses, no early information is available in the literature, but first reports started appearing in about 1997. As from about this date reports on Marathon® (DePuy), XLPE® (Smith & Nephew), Longevity® (Zimmer), Durasul® (Sulzer) and Crossfire® (Stryker) were reported in the literature.[7] However, no long-term results from any of these companies were reported and indeed no such results were available!

Although the initial research and clinical trials in South Africa were reported extensively in the international literature, both in the fields of radiation science and orthopaedics, surprisingly little reference was given to this earlier work in even recently published papers in the USA in this regard.[8] Author 2 indeed recently referred to this situation in reviewing such a paper.[9]

The radiation crosslinking techniques of the UHMWPE

The Gammalink® technique involves the radiation crosslinking of the *finally machined* UHMWPE prostheses. The process is thus applied to the post-manufactured prostheses and thus allows for the radiation crosslinking of any finally machined UHMWPE implant.

In the techniques developed in the USA, the crosslinked prostheses rely on the *prior* radiation crosslinking of the UHMWPE *feedstock polymer* only available in solid cylindrical or blocked format, followed by the machining of the implant from the crosslinked polymer. According to Murotoglu, Sulzer at that time even went back one step and crosslinked the polymer in resin pellet [or powder] form, prior to the moulding thereof into acetabular-cup form.[10] In this way large numbers could be produced; however, it resulted in a completely different homogeneous (and softer) cup, according to Murotoglu. It therefore follows that it would be scientifically wrong to extrapolate the excellent results observed with the Gammalink® technique to that of the Sulzer cups. In this regard Sulzer need to test the modified polymer themselves, both mechanically and through long-term clinical testing.

Radiation crosslinking environment applied in techniques

The Gammalink® technique involves the radiation crosslinking of the prostheses *in the presence of a mediating gaseous* crosslinking agent or a mixture of such mediating gases. This implies that the *outer surface* (load-bearing area) is crosslinked to a much higher degree because of the diffusion-controlled nature of the gas into the outer 300 μm of the device.[4]

In the techniques developed in the USA, the radiation crosslinking of the bar feedstock material is carried out in air or in an inert nitrogen atmosphere in order to limit the radiation-induced surface oxidation of the feedstock material. The outer surface of the feedstock material is subsequently machined off to remove the oxidised surface – something which could have a detrimental impact on the wear characteristics of the implant should annealing of the polymer not be carried out.

Distribution of crosslink density in treated UHMWPE prostheses

Following from the radiation crosslinking of the UHMWPE prostheses in the presence of a mediating gas or gas mixture, the *crosslink distribution* in the Gammalink® technique in the implant is largely *diffusion controlled* resulting in an *inhomogeneous* nature of the crosslink distribution in the implant – a high degree of crosslinking on the surface, decreasing into the body of the device. This diffusion-controlled degree of crosslinking is superimposed on the normal attenuation of the gamma radiation through the prostheses. This higher degree of crosslinking on the surface of the prostheses results in an enhanced visco-elastic surface of the prostheses – similar to case hardening in metals. Initial machine marks on the inside bearing surface of UHMWPE acetabular cups were distinctly noticeable even 14 years after implantation by authors 2 and 3 – without any initial *running-in* wear associated with an initial period of high wear, something often reported for prostheses crosslinked by the techniques developed in the USA.[11]

In the absence of a gaseous crosslinking agent as is the case with the techniques developed in the USA, the crosslink distribution is controlled by the *attenuation* of the radiation in the polymer. As this effect is far less prominent than the corresponding situation in the Gammalink® technique, a largely *homogeneous* crosslink distribution is achieved in these techniques without the enhanced surface crosslinking and the associated visco-elastic characteristics of the prostheses.

Annealing of crosslinked UHMWPE

In order to reduce the post-irradiation long-lived free radicals in the treated prostheses, the prostheses were initially annealed at 80 °C for 8 h in vacuum or analytical nitrogen and allowed to cool down to ambient temperatures.

Early in 1998 a more efficient annealing technique was introduced commercially in South Africa in which the annealing is carried in the presence of the mediating gas without exposing the irradiated devices to air prior to the annealing step. This annealing technique has been used routinely on all Gammalink® prostheses since 1998.

It was shown than an additional 35% decrease in the melt-flow index (MFI) in the irradiated polymer on the surface is obtained through this annealing procedure alone – resulting in complete annihilation of the residual long-lived free radicals in the outer 300 μm of the polymer surface, an additional enhancement of the inhomogeneous nature of the crosslink density, and the subsequent improvement of the surface wear characteristics of the prostheses.

In most of the current USA techniques the radiation crosslinked UHMWPE is remelted or annealed in an inert atmosphere to remove the long-lived free radicals in the bar feedstock material. In some instances the outer surface is machined off to remove the oxidised outer surface of the feedstock polymer. This procedure will only expose the remaining long-lived free radicals in the polymer to air – with the same oxidative degradation thereof. In many cases this results in a *running-in* wear in which the initial wear is relatively high, followed by a period of less wear.

All indications are that these observations result from the initial surface oxidation of the UHMWPE in the presence of air, followed by the normal lower wear emanating from the crosslinking deeper into the polymer surface.

Inert packaging of crosslinked prostheses

Since 1998 the double packaging of the prostheses treated through the Gammalink® technique has been carried out in high-purity analytical grade nitrogen to limit any radiation degradation of the polymer surface during the gamma sterilisation step. For simplicity and packaging integrity reasons, laminate polymer bags (PE/Polyester, 90 μm) are used in both the hermetic sealing of the primary and secondary packaging.

In order to avoid the possible radiation-induced degradation of the prosthesis, a number of USA manufacturers use ethylene oxide or gas plasma for sterilisation. It was noted, however, that Stryker and Kyocera also use gamma sterilisation in the presence of nitrogen.

Sterilisation methods

In the case of the prostheses treated by the Gammalink® technique, a minimum absorbed gamma irradiation dose of 25 kGy is applied in the terminal sterilisation of the double-sealed prostheses. It is reported that the radiation crosslinked prostheses in the USA are sterilised by ethylene oxide (ETO), gas plasma or gamma radiation at doses from 25 to 40 kGy.

General comments

The Gammalink® technique is characterised by its excellent clinical track record over more than three-and-a-half decades. Over this period no wear was observed in 70% of cases between 10 and 33 years (mean 20.12 years). A further 13% of the prostheses had minimal wear and showed excellent results. In one bilateral case there was no wear after 35 years employing the latest digital X-ray techniques.[12] No brittleness, fractures or delamination was encountered in these series. The technique is simple and easy to control and results in a very high degree of process assurance and corresponding attractive economics. The particular clinical success achieved with the Gammalink® technique in the radiation crosslinking of UHMWPE hip prostheses goes a long way to solve the problem of wear in joint replacement surgery in order to render a permanent solution. The problems experienced with metal-on-metal hip prostheses will in all probability lead to an enhanced swing to polyethylene acetabular cups in the case of hip implants.[13]

In contrast, many of the crosslinking procedures developed in the USA have limited track records with a number of reported failures.[14,15] These techniques are generally complex requiring tightly monitored controls – impacting on the economics thereof.

Conclusions

1. The Gammalink® crosslinking technique of UHMWPE prostheses was developed and clinically introduced in South Africa by a multi-disciplinary team more than two decades before any such work was reported anywhere else in the world.
2. To date a total of more than 12 000 different types of prostheses were treated in South Africa – applied to a number of locally manufactured devices as well as imported well-known international brands.
3. The use of a gaseous mediating agent during the crosslinking process ensures that the outer surface of the UHMWPE (300 μm) is highly crosslinked with no possibility of any surface oxidation.
4. No surface treatment is required in the case of the Gammalink® technique as no oxidation of the UHMWPE can take place during the radiation treatment and prior to the annealing. In addition, extensive measurements indicated that no dimensional changes of the prostheses take place during the radiation crosslinking step.
5. The inhomogeneous nature of the crosslink distribution achieved in the Gammalink® technique has a fundamental impact on the visco-elastic properties of the crosslinked device. A situation similar to case hardening in metals is obtained where the highly crosslinked wearing surface of the UHMWPE prosthesis is greatly improved, without sacrificing the advantageous visco-elastic properties of the UHMWPE.
6. In a follow-up period of more than 35 years of clinical results in South Africa, not a single mechanical failure of a UHMWPE implant was reported, due to the Gammalink technique.[4] It is, however, well known that some crosslinked acetabular cups in the USA exhibited major mechanical failures only months after implantation. Remarkably, cup wear in the SA series was eight times lower than the world standard for non-crosslinked cups.[11]
7. The Gammalink® annealing technique employed commercially in South Africa since 1998 largely simplifies the entire process. It has the added benefit that it results in the complete annihilation of the long-lived free radicals on the outer 300 μm of the prostheses and an additional enhancement of the inhomogeneous crosslink density, as well as an additional improvement of the surface wear characteristics. It was noted that this technique was patented in the USA round about 2003 – more than five years after it was introduced commercially in South Africa.
8. The primary packaging of the prostheses in a high-purity inert gas enables the use of highly reliable gamma sterilisation without running the risk of the radiation-induced oxidation of the surface of the implant.
9. As the laminate packaging used in the Gammalink® technique has a very high packaging integrity, it obviates the need for a specified shelf life – provided the integrity of the packaging is maintained.
10. The development work and ensuing clinical track record of the Gammalink® technique is a good example of what can be achieved through the collaboration of experts in different disciplines.

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