NEW POLYS FOR OLD: *CONTRIBUTION OR CAVEAT?*

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A REALITY CHECK

The enduring success of the low friction arthroplasty first advanced by Sir John Charnley as a solution for severe hip arthritic problems may be appreciated from the fact that in 1999 over 500,000 hip and knee arthroplasties were performed in the United States. The percentage of aseptic loosening attributed to polyethylene debris-induced osteolysis is in the single digits for most contemporary series with some reports describing 20 to 30 year patient survivals. (Figure 1)

(a) (b)

Figure 1: *Charnley cemented hip replacement radiographs. (a) Immediate post-operative; (b) 25 years post-operative.*

Gamma irradiation in air has until recently been the predominant method of ultra-high molecular weight polyethylene (UHMWPE) component sterilization and despite current concerns, represents the only gold standard against which contemporary material improvements will be measured over time.

STRUCTURE, STERILIZATION AND STORAGE MECHANICS

The UHMWPE used in hip and knee components results from polymerization of ethylene gas into a fine resin powder of sub-micron and micron size distribution. It is consolidated using ram extrusion or compression molding techniques. Structurally the polymer is made up of repeating carbon-hydrogen ($-CH_2-$) units that are arranged in ordered (crystalline) and disordered (amorphous) regions. Irradiation to achieve component sterilization breaks the polymer chains creating free radicals which, in an air environment combine with oxygen facilitating ongoing oxidative degradation of the polymer. (Figure 2)

Continued exposure to oxygen through prolonged component shelf storage in air before clinical use results in a progressive stiffening and embrittlement of the polymer, reducing wear resistance and fatigue strength. This is thought to represent a major contributing factor influencing *in vivo* polymer failure. (Figures 3 & 4)

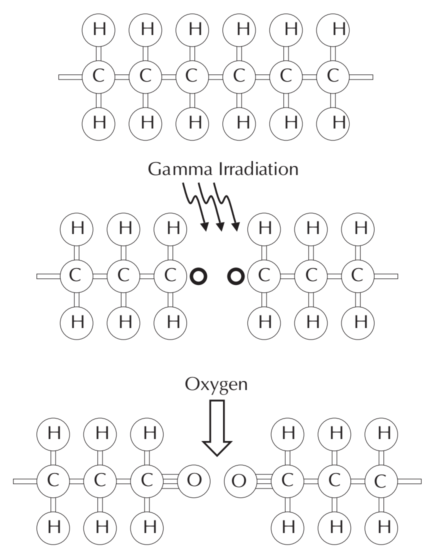


Figure 2: *Depicted polymer chain breakage following irradiation in air and combination with oxygen facilitating oxidative degradation of UHMWPE.*

STRUCTURE, STERILIZATION AND STORAGE MECHANICS

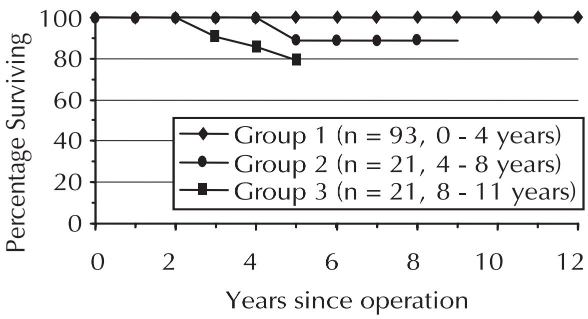


Figure 3: *The influence of shelf storage on knee plateau survival following gamma irradiation in air. From Bohl, et al., CORR 367:28-38, 1999.*

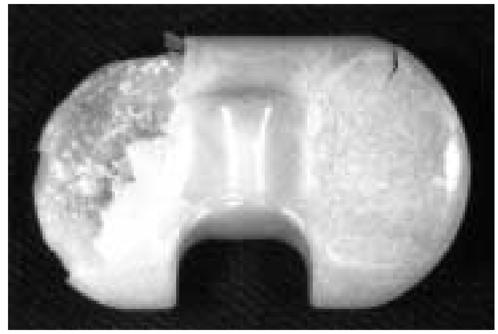


Figure 4: *A Group 2 plateau retrieved 3.8 years after implantation following shelf storage of 7.6 years. Gross delamination and pitting are observed and are characteristic of fatigue failure.*

Besides reacting with oxygen, however, free radicals can also combine, creating cross-links between adjacent molecules. Bench testing suggests that these cross-links improve wear performance. Eliminating oxygen from the sterilization process by employing inert gas or vacuum environments further contributes to this improvement.

Alternative sterilization methods employing ethylene oxide or gas plasma without ionizing radiation avoid oxidation, but do not realize potential wear performance benefits resulting from increased cross-linking. (Figure 5)

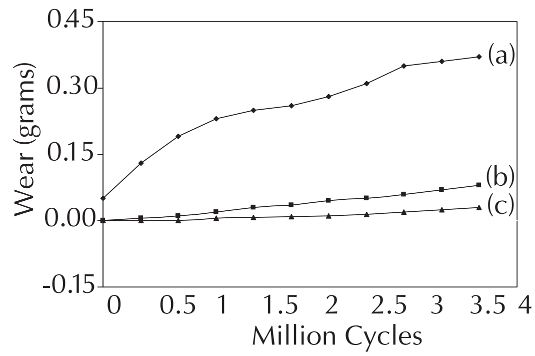


Figure 5: *Hip simulator weight loss comparison for aged (25 days at 78°C in O_2) compression molded cup components. (a) air irradiated; (b) ethylene oxide; and (c) vacuum irradiated with barrier packaging. From Greer, et al., Trans ORS 23:52, 1998.*

LESSONS FROM THE PAST

Previous attempts to improve UHMWPE performance have included carbon fiber reinforcement (Poly-2) and more recently polymer reprocessing to enhance mechanical properties by hot isostatic pressing (Hylamer). The former was withdrawn due to an unexpectedly high wear rate (Figure 6) while the latter, especially when sterilized by radiation in air, has been linked to debris-induced osteolytic response in early reports. (Figure 7)

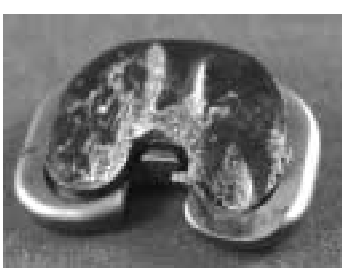


Figure 6: *Five-year retrieval of a failed Poly-2 tibial insert.*

Figure 7: *Three-year retrieval of a failed Hylamer acetabular cup insert.*

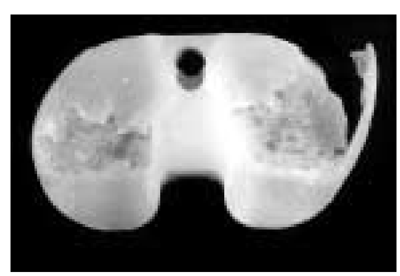


Figure 8: *Six-year retrieval of a heat pressed tibial component.*

LESSONS FROM THE PAST (Cont.)

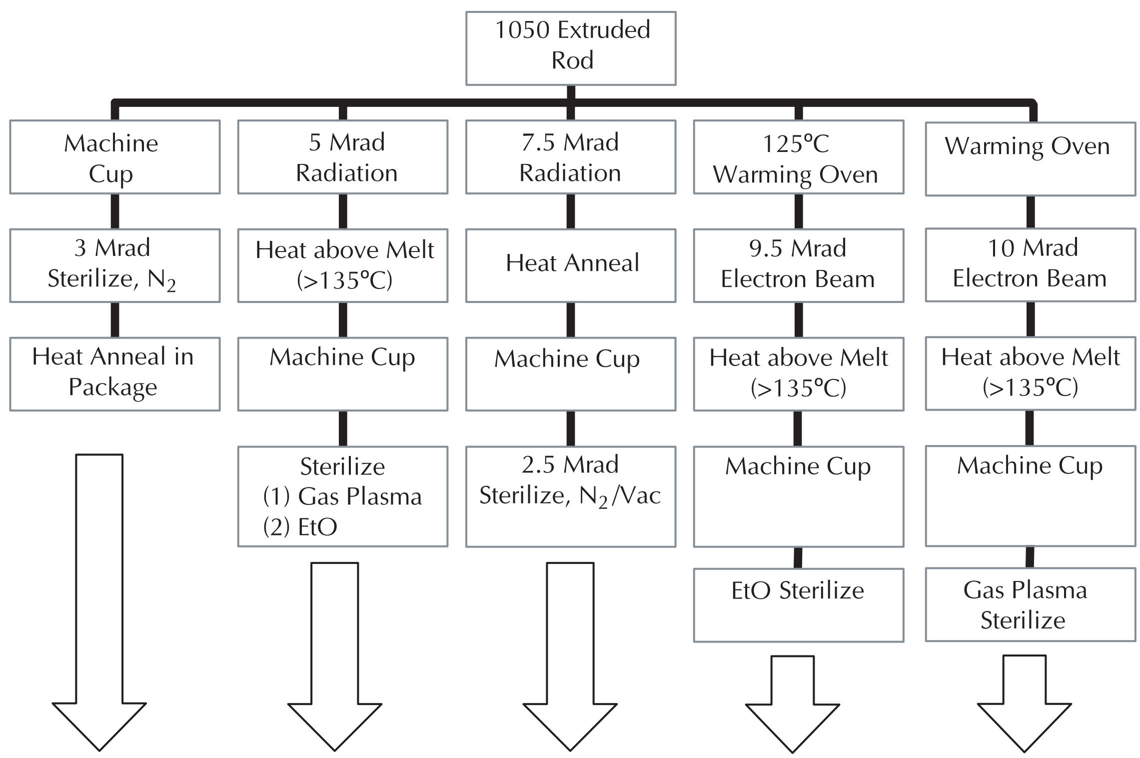
Heat pressing was yet another attempt to improve articular surface finish, but was associated with polyethylene fatigue and early delamination. (Figure 8)

These findings suggest that the pre-clinical evaluations of the above polyethylenes did not fully predict performance *in vivo.*

CROSS-LINKED POLYETHYLENES

The new generation of cross-linked polyethylenes represents a class of emerging UHMWPE alternatives whose common denominator is an appreciation of the importance of increased cross-linking and minimizing oxidative degradation to reduce wear. Both chemical and thermal/radiation processing solutions have been advocated, a number of the latter receiving recent FDA clearance allowing commercial product distribution.

Process differences include: 1) heating above or below the melt temperature of the polyethylene, 2) radiation source, 3) dose level and 4) end point sterilization. (Figure 9)



Process Name	**Heat Stabilized**	**CISM** (Cold Irradiated Subsequent Melt)	**CIAN** (Cold Irradiated Annealed Non-melt)	**WIAM** (Warm Irradiated Adiabatic Melting)	**WISM** (Warm Irradiated Subsequent Melt)
Product Name	*Duration™*	*(1) Marathon™* *(2) XLPE™*	*Crossfire™*	*Durasul™*	*Longevity™*
Company	*Stryker Howmedica Osteonics*	*(1) DePuy/J&J* *(2) Smith+Nephew*	*Stryker Howmedica Osteonics*	*Sulzer*	*Zimmer*

Figure 9: *Current methods used to manufacture moderate to highly cross-linked polyethylene.*

CROSS-LINKED POLYETHYLENES (Cont.)

In general, increasing the radiation dose dramatically reduces polymer wear in laboratory hip joint simulation. (Figure 10) Free radical suppression through kinetic recombination at increased temperature in an oxygen-free environment or quenching through re-melting seeks to stem the oxidation process.

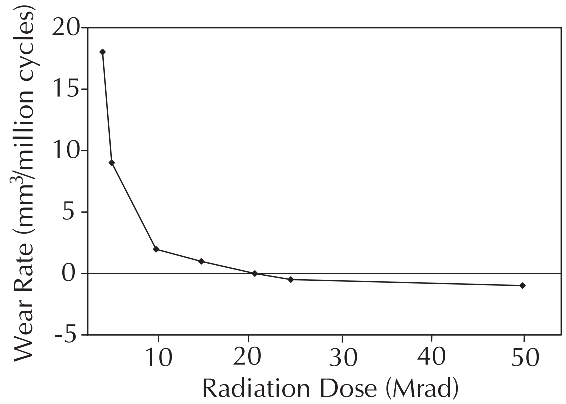
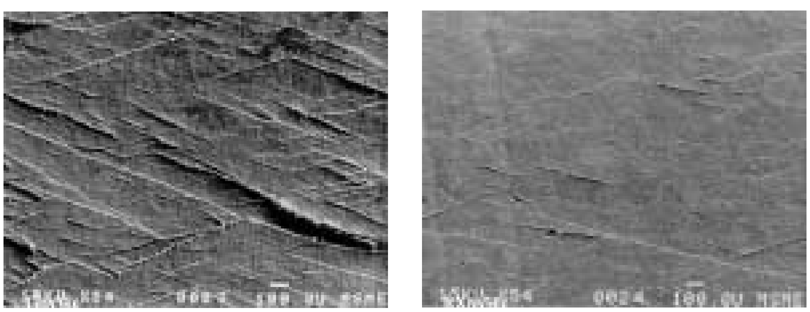


Figure 10: Mean acetabular cup wear rates versus gamma dose level. From McKellop, et al., Trans ORS 23:98, 1998.

NOTES OF CAUTION

However, the above processes also change either the amorphous or both the amorphous and crystalline regions of the resulting polymers, affecting mechanical properties and potentially reducing fatigue characteristics. Fatigue damage is a factor associated with high cyclic stresses in non-conforming UHMWPE knee components. It is not known how these polyethylenes will perform in knees. Current market application is primarily limited to acetabular components with the exception of the October 2000 FDA clearance of Durasul™ for knee use.

There is some laboratory evidence to suggest that increased cross-linking may decrease resistance to fatigue crack propagation (Figure 11), a finding that could have implications for some modular acetabular cup designs. (Figure 12)



(a) (b)

Figure 11: SEM micrographs of polyethylene fatigue fracture specimens. (a) gas plasma sterilized demonstrating ductile tearing associated with plastic deformation and slowing fatigue crack growth; (b) radiation cross-linked demonstrating the relative absence of ductile tearing mechanisms. From Pruitt, et al., J Biomed Mater Res, 46:573-581, 1999.

Figure 12: Crack propagation failure of an acetabular cup retrieval that is associated with an inadequate locking mechanism design.

Currently, there is no direct clinical experience to support the promised long-term *in vivo* integrity suggested by laboratory evaluation for the cross-linked polymers being marketed today.

The absence of long-term clinical performance information for highly cross-linked UHMWPE components prompted the Medical Devices Agency of the United Kingdom in June 1999 to issue a Safety Notice (MDA SN1999(23)) advising caution in their use and careful patient monitoring.

TAKE HOME MESSAGE

- For the past three decades UHMWPE hip and knee components have been predominantly sterilized by gamma irradiation in air, and have shown remarkable overall resilience in clinical function.
- Nevertheless, aseptic loosening attributed to polyethylene debris induced osteolysis is of contemporary concern. Particularly as the indications for total joint replacement expand to younger patients and life expectancy increases, the interest in alternative bearing materials has accelerated.
- It is now known that irradiation in an environment where oxygen is present encourages UHMWPE component oxidation resulting in embrittlement and a decrease in wear performance. This process continues when components are shelf-stored in air or in permeable packaging for prolonged periods before use.
- Sterilization in oxygen free environments with barrier packaging and shelf dating reduce the prospect of material compromise.
- The use of ethylene oxide and gas plasma as alternative sterilization methods avoid oxidative degradation, but do not realize potential benefits with respect to polymer wear reduction derived from cross-linking.
- Recently a number of "improved" polymers have emerged whose common benefit resides in increased cross-linking concurrent with minimizing oxidation. Pin-on-disk testing has not been shown to predict *in vivo* performance, but hip simulator models suggest a significant reduction in wear with these new polymers.
- These processes, however, change the chemical structure of the polymer affecting both static mechanical properties and fatigue characteristics.
- A number of these polyethylenes have received FDA clearance and are commercially available in the absence of clinical reports.
- Corporate responsibility to assess short-term performance via evidence based studies is requisite and should be a consideration in surgeon selection of highly cross-linked polymer components.