Wear of Human Joint Prosthetic Devices of Ultra-High-Molecular-Weight Polyethylene (UHMWPE) a Result of Mechanical Compression

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For more than 30 years, ultra-high-molecular-weight polyethylene (UHMWPE) has been used as a bearing material in total-joint-replacement prostheses. Such orthopaedic implants usually comprise a metal (typically a cobalt-chromium alloy) or ceramic component that articulates against a UHMWPE component in vivo use. It has been well established that the longevity of such implants depends on the wear performance of the UHMWPE components [1, 2]. The presence of particulate wear debris of UHMWPE that is generated due to the sliding of UHMWPE components against the metal or ceramic counter-face has been linked to complications such as tissue inflammation, bone loss (or osteolysis), and implant loosening. Osteolysis resulting from wear of UHMWPE is recognized as the leading problem in orthopaedic surgery today. Because de wear volume influence the mechanical performances of a prosthetic device in this paper is studied the variation of the wear volume depending on the number of cycle motion and the time.

Keywords: polyethylene, prosthesis, cross-linked, wear

Ultra high molecular weight polyethylene (UHMWPE), also known as high modulus polyethylene (HMPE) or high performance polyethylene (HPPE), is a thermoplastic. Polyethylene is an organic compound formed by long repeating chains of a single substance: the molecules of the gaseous substance ethylene [2]. The mechanical properties of polyethylene improve slowly with rising molecular weight of the product. A dramatic change in mechanical properties, however, appears when molecular weight of the polyethylene molecule exceeds one million. This appears when more than 35 000 ethylene groups are added together. The molecular weight of the UHMWPE currently used in total joint components varies between 4 to 6 millions. Every such UHMWPE molecule is composed of 160 to 215 000 ethylene groups. It has extremely long chains, with molecular weight numbering in the millions, usually between 2 and 6 million. The longer chain serves to transfer load more effectively to the polymer backbone by strengthening intermolecular interactions. This result in a very tough material, with the highest impact strength of any thermoplastic presently made. It is highly resistant to corrosive chemicals, with exception of oxidizing acids. It has extremely low moisture absorption, very low coefficient of friction, is self lubricating and is highly resistant to abrasion (10 times more resistant to abrasion than Carbon Steel). It is odorless, tasteless, and non-toxic. UHMWPE is a type of polyolefin and, despite relatively weak Van der Waals bonds between its molecules, derives ample strength from the length of each individual molecule. It is made up of extremely long chains of polyethylene, which all align in the same direction. Each chain is bonded to the others with so many Van der Waals bonds that the whole can support great tensile loads [1, 2].

Ultra- High Molecular Weight Polyethylene (UHMWPE) is the current material of choice for use as a bearing surface in total joint prostheses. Total joints with components made of this material can function for more than twenty years if they are well designed and well implanted. However, there is a growing body of evidence showing that wear particles worn off the surface of UHMWPE component may trigger destruction (osteolysis) of the skeleton around the total joint and eventually cause a failure of the whole total joint.

The life span of an artificial hip joint is momentarily at approx. 10 - 20 years [3]. An increase of the life span of the implant can possibly be achieved interlacing or *Cross-linking*. By irradiation cross connections between the linear, crisscrossed carbon chains are produced.

Cross linking has been shown to be an effective way of improving the wear resistance of UHMWPE as shown by hip simulator tests for both rough and smooth metallic counter face. Cross linking is achieved either by gamma or electron beam irradiation under inert conditions, followed by a heat treatment either above or below the UHMWPE melting point. Thus free radicals are formed by irradiation and react when heated to produce crosslink's. Alternatively chemical cross linking can be achieved by addition of peroxide to the UHMWPE resin prior to moulding and irradiation. These techniques are also effective in improving the oxidation resistance of UHMWPE as free radicals, which are produced during the irradiation processes, are generally consumed by the cross linking reactions and therefore unavailable for reaction with oxygen [5,6].

The mechanism of cross-linking is the following: The irradiation knocks an electron out of the Hydrogen atom. The Hydrogen atoms then wander out of the polyethylene molecule as free radicals (blue balls with red hats in the picture). This happens simultaneously on several places in several UHMWPE; the carbon atoms that are lacking their Hydrogen neighbors keep "free hands" out to find a new neighbor. The opposite "free hands" in two molecules meet and cross-link one UHMWPE molecule to another on several places. The degree of cross-linking increases with the dose of absorbed irradiation.

The wear resistance of irradiated material in a hip simulator is dependent on the irradiation dose:

4 Mrad – the maximal radiation dose used for sterilization of the material produces 80% reduction of wear in the irradiated UHMWPE

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Table 1
THE MECHANISM OF CROSS-LINKING

$R \xrightarrow{\gamma} R\bullet$	Initiation
$R \xrightarrow{O_2} RO_2\bullet$ $RO_2\bullet \xrightarrow{RH} RO_2H + R\bullet$	Propagation
$RO_2H \longrightarrow RO\bullet + \bullet OH$ $RO\bullet \leftrightarrow ROH + R\bullet$ $\bullet OH \leftrightarrow H_2O + R\bullet$	Chain branching
$RO_2H, RO_2\bullet, R\bullet \rightarrow$	Process leading to Scission and cross-linking
$2RO_2\bullet \rightarrow RO_2R + O_2$	Termination

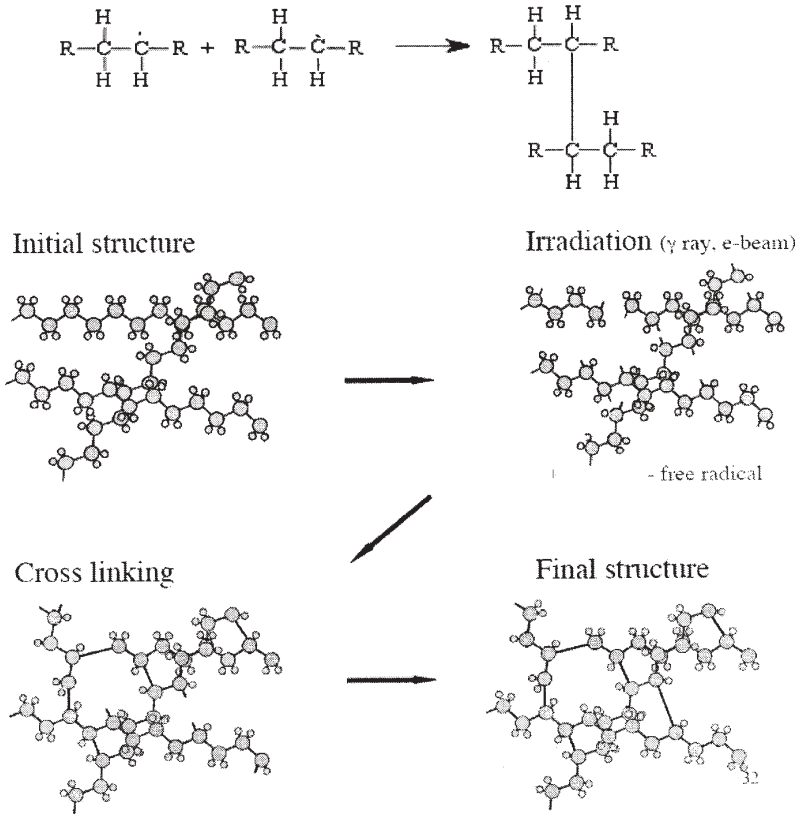

Fig. 1. The schematic model of internal structure of ultra height molecular weight polyethylene before and after cross-linking process

10 Mrad – the maximal dose used for cross-linking of the UHMWPE by some manufacturers causes 95% reduction of wear in the irradiated UHMWPE.

The cross-linking of UHMWPE results in an interpenetrating network of high-molecular-weight polyethylene chains, with the potential benefit of increased strength in the interfacial region between resin particles of polyethylene components. Incomplete consolidation of resin particles has been observed in components of UHMWPE, and is believed to contribute to wear [5].

Although cross-linking of UHMWPE has been shown to improve performance in hip-simulator wear tests, mechanical tests conducted on cross-linked material have shown a reduction in several mechanical properties including Young's modulus, yield stress, ultimate tensile stress and strain-to-break. These results appear contradictory, since it is generally believed that the toughness of a polymer correlates with its wear performance.

Experiment, material and method

Despite its superior mechanical performance, UHMWPE standard is not a perfect material. It is subjected to fatigue failure and it produces too many wear particles. Wear mechanism is based on the sudden variation of molecules orientation in polyethylene structure during the compression load function of movement direction. The experimental procedure is based on tribological tests on a spine prosthetic device of polyethylene with a medium load by 1015 N, during 1, $02 \cdot 10^{6}$ s and in motion of flexion-extension. The prosthetic device is moving in x and y direction and so that at the polymer structure level are made important modifications these are the progenitor of wear mechanism.

Through cross-linking the ultra height molecular weight polyethylene get a structure much more densely which increases the wear resistance but the direction of motion modify the internal structure of polyethylene molecule and this is one of some factors on which depends the wear process. In figure 1 is schematically represented the model of internal structure of ultra height molecular weight

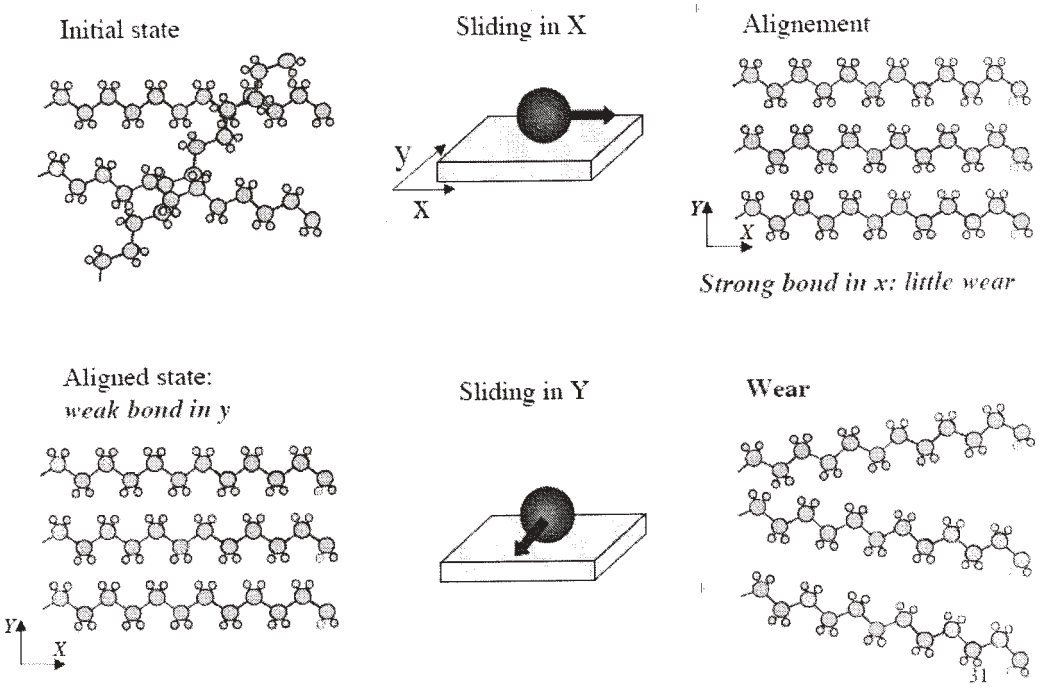

Fig. 2. The orientation of the molecules from internal structure of UHMWPE in multidirectional sliding

polyethylene and the structural modification of molecule after cross-linking process.

Because the prosthetic device is tested on motion in direction x and in y and the applied force load is by 1015 N, then in polyethylene structure happened some important modification. Held the account of the studies from literature [3, 4, 5] which sustain the idea that, although after cross-linking the molecular structure of ultra height molecular weight polyethylene is compact during the motion in one direction x or y, the molecules have tendency to orientate on the motion direction just as follows in figure 2.

According to figure 2 the polymeric material movement on the direction x, orientates the molecules on this direction and the intermolecular connections on the direction x are very strong, but in y direction the molecular connection are thin so that, these connection can tear to the motion on y of the prosthetic component and because the molecules have tendency of orientation on this direction and are so thin, a rupture is produced and appears the material wear. The wear volumes is an important parameter because this dictates the life time of implant and then are calculate two elemental parameters: the volume of material loose after wear and the variation of polymeric prosthesis height.

The variation in time of wear volume is:

$$V(t) = k_1 \cdot \frac{N \cdot L_f}{3 \cdot p_c} = k_1 \cdot \frac{\overline{R}(t) \cdot |\overline{\omega}(t)| \cdot (r_s \cdot 10^{-3}) \cdot t}{3 \cdot p_c} \quad (1)$$

Where: k_1 – wear volume coefficient (a dimensional);
$\overline{R}(t)$ - the medium value of applied load [N];
L_f – friction length [m];
p_c = 22MPa –flow pressure of UHMWPE

$$L_f = |\overline{\omega}(t)| \cdot (r_s \cdot 10^{-3}) \cdot 1{,}02 \cdot 10^6 \quad (2)$$

Are now:
-the average value of applied load is $\overline{R}(t) = 1015N$;
The average values of angular speed is $|\overline{\omega}(t)|$ 1,10556rad/s and all tests are made during a period of 1, $02 \cdot 10^6$ s, then V (t) is calculate.

For calculation the height variation of wear out polymer are used classical formula, in conformity with [6]:

$$h(t) = k \cdot p(t) \cdot L_f = k \cdot p(t) \cdot |\overline{\omega}(t)| \cdot (r_s \cdot 10^{-3}) \cdot t \quad (3)$$

$$p(t) = \frac{\overline{R}(t)}{2 \cdot \pi \cdot h_1(t) \cdot r_u} \quad (4)$$

where:
k – linear wear coefficient [mm^3/N×m];
p (t)–the contact pressure [N/mm^2].

Results and discussion

According to relation 1, the variation of wear volume is linear if the wear coefficient is considered constant, the other parameters being constants as average values of some variable parameters, then the only variable parameter is the time shown in figure 3.

Substituting the parameters in ecuations (3) and (4), the variation of the maximum height of wear-out polimeric component of prosthesisi is linear, according to figure 4.

From the calculations and the charts made in Math Cad can be seen that, upon the succeded experiment, the variation of the volume of the worrn-out material and the height of the polymeric component are linear in time, therefore the wear shall be linear. The valoric interval is containend in the range of values mentioned the international literature.

Considering a cycle of motion per second, the polymer has been tested for one million twenty cycles of operation and it was obtained the chart from figure 3; to compare the results with the literature we used the chart for one million five hundred cycles of operation tests (fig. 5).

The charts are nearly identical, wear variation is show and it is in the prestablished limits, which demonstrates that the prototype tested may have a 20 years duration of life.

Conclusions

The ultra high molecular weight polyethylene used like spine implant behaved in the similar way like the other

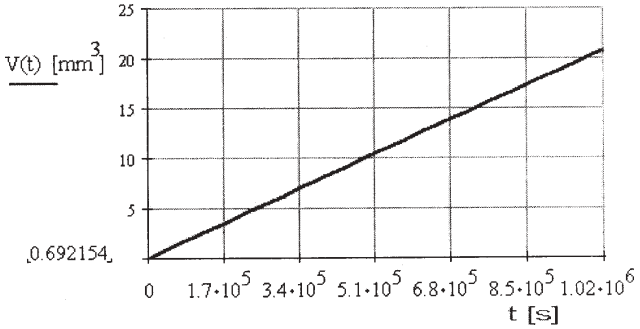

Fig.3. The variation of wear volume function of time

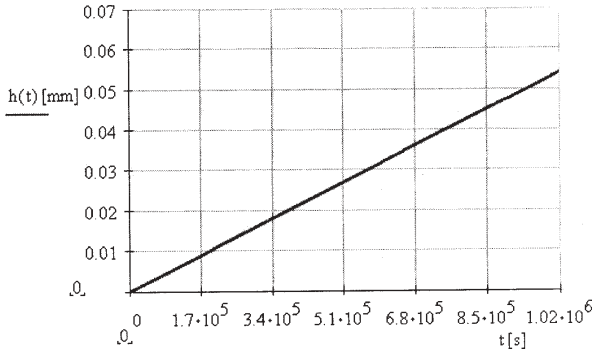

Fig. 4. The height variation of the polymeric component of prosthesis

implants that used the sa me material but for the other joint of body.

The volume of worn-out material and the height of the prosthetic component worn-out vary linear with time, during the testing of the polymeric prosthetic component.

The degree of ultra high molecular weight polyethylene wear depends on the time the prosthetic component was tested and on the number of motion cycles.

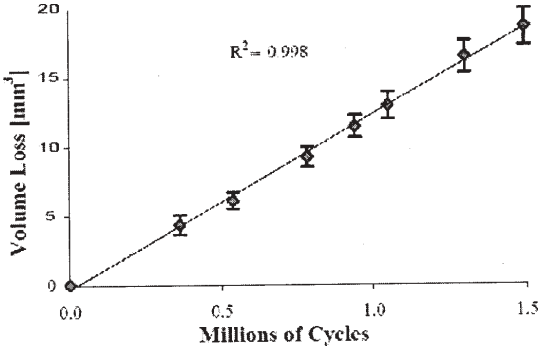

Fig. 5. The variation of the volume of material worn-out of a polymer component from prosthesis for a one million five hundreds of cycles operation [5]

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