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Femoral prosthetic heads and their significance in polyethylene wear

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Abstract We used scanning electron microscopy to perform an ultrastructural analysis and two optical interferometric profilers to measure roughness on 40 prosthetic femoral heads. We expressed roughness as Ra (roughness average) value and Rsk (roughness skewness) value. Our results show that in order to obtain an ideal surface finish a low or not very high Ra value and a negative Rsk value are needed. The presence of depressions or holes (rather than scratches) with smooth (rather than sharp) edges seems to improve the lubrication and wettability properties.

Résumé Nous avons utilisé la microscopie électronique à balayage pour une étude ultrastructurale et mesuré par interféromètres à lecture optique la rugosité sur 40 têtes fémorales prothétiques. Nous avons exprimé la rugosité comme Ra (la moyenne de la rugosité) et Rsk qui est une valeur des asymétries du profil par rapport à la ligne moyenne. Nos résultats démontrent que pour obtenir une surface idéale, un bas ou pas très haute valeur de Ra et une valeur négative de Rsk sont nécessaires. La présence de dépressions ou vallées (au lieu de griffes) avec un bord lisse (au lieu de tranchant) paraît améliorer la lubrification et les propriétés de mouillabilité.

Introduction

The bearing surfaces of prosthetic joints are recognized as being the main source of wear debris that is responsible for the inflammatory reaction [1, 10] in many instances of implant failure. Most often the ultra high molecular weight polyethylene (UHMWPE) particles are responsible for this process [9, 10].

The effect of gamma irradiation on the oxidation process of free radicals in carbon chains is assumed to be

the major cause of polyethylene (PE) degradation leading to cracking and delamination [9]. Changes have therefore been introduced into the process of sterilization and packaging of PE components [5] that seem to have significantly improved the endurance of the material and limited the wear process. Nevertheless, all the efforts to improve PE may be in vain if the opposite bearing surface is rough or has a poor surface finish capable of rapidly wearing a softer counterpart. The question is what can be considered an adequate surface finish?

Roughness average (Ra) is the most popular value for determining surface finish. It simply describes the distribution of peaks and valleys on the considered surface. A surface with a low Ra is considered to be excellent, and surfaces with higher Ra as fair or poor, when compared to the ISO standard. Unfortunately, the Ra does not indicate if roughness is caused by peaks or valleys, or the relationship between these. Therefore, a bearing surface with a high Ra may be misleadingly considered poor. Roughness determined by peaks elevating from the surface will be aggressive and fast wearing, while the same Ra determined by valleys will increase lubrication, optimizing the coupling of the surfaces and not affect wear. For this reason other values have been introduced in the evaluation of a surface. This paper aims to define the concept of roughness in order to understand the role of femoral head components in PE wear.

Materials and methods

We evaluated 8 different femoral heads produced by 5 different orthopaedic companies. Each of the 8 femoral heads was studied in 5 samples of the same lot, making a total of 40 heads. They were all heads with a diameter of 28 mm. Five were metal heads: 3 cobalt chromium molybdenum (CoCrMo), 1 CoCr with surface treatment with nitrogen ions (CoCrNi), and 1 titanium with a ceramic covering (TiNb-ON); 3 were ceramic heads: 2 zirconia (ZrO_2) and 1 alumina (Al_2O_3).

When the heads were removed from their sterile package an ultrastructural analysis was carried out by using a scanning electron microscope (SEM) (JSM 840 A JEOL).

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Fig. 1 Graphic presentation of *Rsk* value

Fig. 2 SEM observation of CoCrMo femoral head with some imperfections (1000×)

Roughness was measured by utilizing two separate devices: an interferometer Form Talysurf (Rank Taylor Hobson) with a diamond tracer and an optical reading interferometer RST Plus (Wyco Corporation). Both devices repeated each test and considered the same value more precisely: *Ra* (roughness average), *Rq* (root mean square roughness), *Rp* (maximum profile peak height), *Rv* (maximum profile valley depth), *Rt* (maximum height of the profile), *RzDIN* (average maximum height of the profile), *Rsk* (roughness skewness), *Rpk* (reduced peak height), *Rk* (core roughness depth), *Rvk* (reduced valley depth), *Mr1* (peak material component), *Mr2* (valley material component), proving how accurately a surface can be studied. For this study, attention was focused on two main values: *Ra* and *Rsk* [2] considered, in our experience, the most significant parameters in relation to wear.

Roughness average (*Ra*) represents the average of the absolute distance from the baseline with no indication of the algebraic position of the deviation. Roughness skewness (*Rsk*) represents the deviation from the average baseline where positive *Rsk* indicates a majority of peaks on the surface and negative *Rsk* indicates a majority of valleys (Fig. 1).

Results

Scanning electron microscopy

CoCrMo heads showed shallow linear scratches casually distributed on the surface. Some samples of the series were irregular with more imperfections on the pole than at a distance of 30° from this. Others showed deeper scratches easily detected at 1000 times magnification (Fig. 2).

Different aspects were noticed in the CoCr heads with surface treatment with nitrogen ions. They showed a

Fig. 3 SEM observation of TiNb femoral head (1000×)

Table 1 Mean average of *Ra* in four measurements of five samples of the same lot

Type of prosthetic head	Femoral head	<i>Ra</i> value (μm)
Ceramic	Al ₂ O ₃	0.0129
Ceramic	1ZrO ₂	0.0152
Ceramic	2ZrO ₂	0.0157
Metal	CoCrNi	0.0196
Metal	CoCrMo	0.0204
Metal	1CoCr	0.0208
Metal	2CoCr	0.0675
Metal	TiNb	0.0718

Table 2 Mean average of *Rsk* in four measurements of five samples of the same lot

Type of prosthetic head	Femoral head	<i>Rsk</i> value
Metal	CoCrMo	-2.059
Metal	TiNb	-1.662
Metal	CoCrNi	-0.935
Metal	1CoCr	-0.861
Ceramic	2ZrO ₂	-0.351
Ceramic	1ZrO ₂	-0.218
Metal	2CoCr	-0.195
Ceramic	Al ₂ O ₃	+0.090

highly finished surface, where crater formation was equally distributed. In one case detachment of the superficial covering was observed.

The titanium niobium (TiNb) femoral head treated with multi-layered ceramic coating showed a peculiar aspect with deep and large crater formation with smooth edges and multi-directional scratches (Fig. 3). The ceramic heads were more homogeneous and showed numerous small craters and occasional scratches. One zirconia (ZrO₂) head showed a significant crack in the surface in contrast to the high quality of the remaining surface that may suggest a possible origin of known femoral head fracture.

Fig. 4 **a** SEM picture of CoCrMo femoral head before test ($R_{sk}=-2.059$, $R_a=0.00768$) (1000 $\times$). **b** SEM picture of same CoCrMo femoral head after testing in hip simulator (1000 $\times$)

Fig. 5 **a** SEM picture of TiNb femoral head before test ($R_{sk}=-1.662$, $R_a=0.01593$) (1000 $\times$). **b** SEM picture of same TiNb femoral head after testing in hip simulator (1000 $\times$)

Interferometer measurements

Measurement of the surface finish confirmed the detected differences between various types of heads and between various samples of the same type. Lower R_a values (Table 1) were generally obtained with ceramic heads, even though alumina components showed a positive R_{sk} value and heads from the two zirconia groups only slightly negative values (Table 2). Surprisingly the CoCr with superficial nitrogen ions showed an R_a value similar to the ceramic heads, but the R_{sk} value was however significantly negative (more valleys than peaks). The TiNb multi-layered ceramized metal heads showed the highest R_a value of all with the paradoxically most negative R_{sk} related to the large amount of crater formation on the surface.

Among the three groups of metal heads from different manufacturers only one showed a high R_a value, but it was also the most negative R_{sk} value. The two remaining groups also showed a high R_a value but with R_{sk} almost positive. Each of the five groups of metal heads showed significant differences in R_a and R_{sk} values among different samples. In the ceramic group the different samples were more homogeneous.

Hip-simulator analysis

Analysis after using a hip-simulator with 3 million cycles in double de-ionized water showed that in 2 CoCrMo heads with similar R_a values but different R_{sk} values UHMWPE debris tended to spread on the surface and to fill the cavities without involving the bearing surface when R_{sk} was slightly negative (Fig. 4).

In the metal head treated with ceramic multi-layer (TiNb), with an R_a value greater than double and an in-

intermediate Rsk value, the debris partially filled the surface craters (Fig. 5).

Discussion

Our study confirms previously reported data that ceramic femoral heads have a higher level of surface finish as compared to metal heads. Our study also proves that different treatments of the surface of metal heads improve the behaviour and make its roughness similar to the ceramic heads.

On the other hand simple statements such as “less roughness – better surface” do not always correspond with reality when dealing with bearing surfaces and wear. It is mandatory to define and characterize the type of roughness in order to predict the capacity of wear of one component and prevent wear of the other.

In an artificial joint, components must work in an “auto-lubricating” environment. The purpose of this lubrication is to reduce the friction torque between the two surfaces. In sealed mechanical system the fluid is capable of preventing contact between the two surfaces, limiting friction and wear. In an artificial joint the lubrication can be obtained by a thin layer interposed between the PE and the “valleys” of the femoral head when these are present [5].

The results of the hip simulator analysis suggest that with similar Ra negative Rsk values provide better lubrication. Furthermore, with similar Rsk, the shape of the craters becomes important in determining aggressiveness. Smooth edges are less detrimental than sharp intersecting linear scratches.

Comparison of our results with those previously reported may lead to the following considerations. Ceramic heads have a more homogeneous surface and are undoubtedly “smoother” and thus less aggressive as confirmed by wear tests, even though, in our opinion, these tests do not always represent what occurs in vivo [8, 11].

Among the ceramic heads those containing zirconia seem to have better qualities than those containing alumina. Although Al_2O_3 heads had a low Ra, they also showed a positive Rsk with prevalence of peaks. This may lead to a higher production of wear debris. Furthermore, ZrO_2 heads are reported to be approximately two times more resistant to fracture [3].

Metal heads have higher Ra values with an inconsistent surface and differ from one another in the same lot. When they have been finished with a relatively high number of depressions (highly negative Rsk value) this may limit the wear of the PE with significant cost benefit and reduced risk of head breakage when compared to ceramic heads.

Metal heads with surface treatment (nitrogen-ions or multi-layered ceramic) may represent an excellent compromise when evaluated by the values of Ra and Rsk. However, they may be prone to detachment of the covering and thus exhibit an increased “third body wear” mechanism. The presence of craters with smooth edges more than sharp linear scratches (Fig. 3) leads to better lubrication, and reduces the possibility of wearing the PE. Moreover, the craters may accept debris of different origin that otherwise might have played a role as a third body between the two surfaces. This type of femoral head probably deserves more attention [6, 7] and should be evaluated in vivo long term.

A well-finished surface may be considered either a very smooth surface with a low Ra or even a rough surface with a moderate high Ra, if this is determined by predominance of valleys. However the optimal ratio of Ra/Rsk remains unknown. The greater knowledge about surface finishing and its role on wear together with the improvements of UHMWPE are encouraging and may give hope for a reduction of implant failures due to material debris.

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