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In situ observation of lubricant film formation in THR considering real conformity: The effect of model synovial fluid composition

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ABSTRACT

The present paper explores the effect of synovial fluid composition on lubricant film formation in hip replacements. The measurements were realized utilizing pendulum hip joint simulator, while the film thickness was evaluated using optical interferometry. Contact couples consisted of metal and ceramic femoral heads articulating with glass acetabular cups. As the test lubricants, various model fluids were employed. Initially, static tests, aimed on the effect of material and load on adsorption, were conducted. It was found that adsorbed film thickness increases independently of the head material. Consequently, swinging flexion-extension experiments were realized, revealing that the film formation is substantially affected by composition of model fluid. The thickest film was observed when higher concentration of hyaluronic acid and phospholipids was applied.

1. Introduction

Hip joint arthroplasty is known to be well-established surgery, substantially improving the life quality of millions of patients [1]. Nevertheless, as the number of young active patients with joint replacements gradually increases [2], it is necessary to ensure sufficient service-life of implants to avoid its failure. Since the most common cause limiting the replacement durability is aseptic loosening [3], an extensive attention of researchers is paid to clarify both wear and lubrication processes inside the artificial joints. For this purpose, various types of commercial, as well as tailor-made simulators have been employed, while it is indicated that the key factor, apparently influencing lubricant film formation and subsequent wear rate, is the composition of model synovial fluid (SF) [4].

Although bovine serum (BS) is widely used as the substitution of human SF for *in vitro* investigations [5], it must be taken into account that the composition of BS and SF is different. While BS is composed of proteins (albumin, γ-globulin) and lipids (cholesterol, triglycerides), SF contains albumin, γ-globulin, phospholipids and hyaluronic acid (HA). Especially HA substantially affects the rheology [6] and; moreover, it has a great impact on lubrication properties of the fluid [7]. However, it was shown by Galandáková et al. [8] that the composition and properties of human SF differ significantly according to factors such as age, body mass index (BMI), or joint condition. Therefore, it is desired to carefully consider the composition of model SF when studying the tribological performance of joint replacements.

Typically, biotribological analysis of hip joints can be divided into two groups. The first group deals with *in vitro* evaluation of wear rate under various operating conditions, and the second one aims on the description of lubrication mechanisms inside the contact. Especially the lubrication processes have not been fully clarified yet. However, such a knowledge can help to understand the interaction of human body with the replacements, leading to the further extension of implant durability eventually. Since numerical analyses suffer from several attributes, such as the shear thinning behaviour of SF [9], or protein adsorption [10], whose simulation is particularly complicated, the main attention is focused on experimental investigations.

The influence of various model fluids on lubricant film formation was introduced by Fan et al. [11]. The authors employed simplified ball-on-disc geometrical configuration, while the contact between the glass disc sliding against the stationary CoCrMo femoral head was observed through microscope. Film thickness was evaluated using optical interferometry method. The experiments were performed in the range of

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speeds from 2 to 60 mm/s and the results obtained for protein solutions were compared with those of BS. Although the protein content was higher in the case of BS, protein solutions formed thicker protein film, in general. When comparing the particular solutions, it was observed that despite lower concentration, the model fluid containing γ-globulin exhibited higher film thickness. Adsorbed protein film at the end of the experiment was examined as well. In that case, the adsorbed layer varied from 20 to 60 nm, while the thinnest film was detected for 25% BS and thickest for the mixture of albumin and γ-globulin in a ratio 2:1.

The study was later followed by Myant et al. [4] who also utilized ball-on-disc device and performed three types of experiments; static adsorption test, pure sliding time test, and pure sliding speed test. As the test lubricants, albumin (10 mg/ml; 20 mg/ml; 30 mg/ml), γ-globulin (6 mg/ml), and 25% BS solution (13 mg/ml) were used. The results of static test at zero speed revealed that the adsorbed protein layer was the thickest (around 30 nm) for γ-globulin solution. On the contrary, independently of protein concentration, adsorbed film was less than 5 nm in the case of albumin solutions. BS film reached approximately 10 nm. The results of consequence time test were in a good qualitative correlation with results of static test, while γ-globulin layer was between 200 and 250 nm compared to 30–40 nm for albumin and BS solutions. Finally, speed test exhibited very complex behaviour of the lubricants with no clear conclusions in relation to particular fluids.

Qualitatively similar results were presented by Parkes et al. [12] for rolling contact. The authors compared solution of albumin (10 mg/ml), γ-globulin (2.4 mg/ml) and protein mixtures of concentrations of 10 mg/ml and 2.4 mg/ml, respectively. The measurements were performed in the same experimental configurations as in the case of previous studies, whilst the applied load (5 N) resulted to a contact pressure of 200 MPa. Rolling speed was set to 10 mm/s and the measurements were realized under ambient temperature. The effect of lubricant pH was examined as well. The measurements were reproduced three times, while it was found that albumin solution formed the thinnest film, which was dependent on pH of the solution. Film thickness for the solution of lower pH (7.4) was relatively unstable and was kept between 5 and 40 nm. An increase of pH to 8.1 caused stabilization of the film; however, the thickness dropped to less than 10 nm. In contrast, γ-globulin exhibited similar behaviour at both pH, while the maximum film was around 350 nm and 250 nm, respectively. In the case of protein mixtures, similar formation as for albumin solution could be observed, while the film varied from 10 to 80 nm at lower, and from 10 to 40 nm at higher pH.

From the above references, it is apparent that the dominant protein leading to increase of film thickness is γ-globulin. However, these implication is based on the observations of simple protein solutions. The authors were not able to distinguish the individual constituents of model SF due to the limitation of the employed measurement method (optical interferometry), which provides just the information about the thickness of the layer between the contact bodies [13]. In our previous studies, we employed the fluorescent microscopy method allowing to separate particular proteins of the model fluid, concluding that under most conditions, the dominant protein responsible for film thickness development is albumin. These findings were revealed for metal [14], as well as for ceramic material of the femoral head [15]. Therefore, it is apparent that the proteins interact and both of them contribute to the film formation, indicating that it is desirable to investigate complex model fluids.

As was mentioned, SF contains not only proteins (albumin, γ-globulin), but also HA and phospholipids. The interaction of individual SF constituents is still a subject of many debates. When investigating the role of individual fluid components, most of the authors focused on the determination of friction of synovial joint cartilage, which is able to operate for many tens of years, exhibiting extremely low friction coefficient [16–18]. Forsey et al. [19] examined friction level in cartilage-cartilage contact focusing on the influence of HA and phospholipids, finding that both the constituents lead to reduction of friction. Moreover, when both the components were combined, further rapid decrease of friction could be observed. Even the specific role of the constituents could be hardly fully explain, the authors suggest that HA targets on chondrocytes promoting the synthesis of new HA molecules. The ability of HA to reduce friction between the cartilage surfaces was later confirmed by Schmidt et al. [20]. Interaction of HA with proteins contained in synovial fluid in relation to friction within cartilage-glass contact was examined by Murakami et al. [21]. The authors confirmed positive effect of HA, while this effect was enhanced when γ-globulin was added into HA solution. In contrast, adding of albumin into HA led to higher friction in all the performed tests. An extensive study clarifying the role of individual constituents and their mixtures on friction in cartilage-glass contact was pronounced in the consequent study [16]. Various test fluids were employed, while the coefficient of friction was studied as a function of sliding distance. Both intact and damaged cartilage were investigated. Focusing on the intact sample and simple solutions of individual constituents, it was found that the lowest friction is exhibited by phospholipids, followed by HA, albumin, and γ-globulin. Almost negligible difference was observed when phospholipids were mixed with albumin and γ-globulin, respectively. Nevertheless, both the proteins led to decrease of friction. Finally, the tests performed with complex fluids revealed that the protein content plays an important role as well. Considering the composition consisting of HA, phospholipids and albumin, it was shown that the friction is substantially lower with increasing protein concentration. The fluid containing 1.4 wt% of albumin exhibited the maximum level of friction equal to approximately 0.01; however, when the content of the protein decreased to 0.7 wt%, the friction increased to around 0.1 at maximum. Very low friction was observed even in the case of HA mixed with phospholipids (≈0.02) and also in the case of HA with phospholipids doped by γ-globulin (≈0.03). As some differences could be observed when focusing on damaged cartilage, the authors concluded that the role of the individual fluid constituents depends not only on the interaction of the molecules, but also on the condition of the cartilage tissue. This was later confirmed by Park et al. [22] who focused on friction measurements considering normal cartilage as well cartilage corresponding to early-stage and advanced-stage of osteoarthritis (OA). Positive effect of γ-globulin and HA on friction was confirmed in the case of advanced OA; however, only a little influence was observed in the case of normal and early-stage OA cartilage.

A detailed insight into an interaction of the individual fluid constituents on friction was given by Seror et al. [17]. The authors concluded that a single constituent is not able to ensure extremely low friction level which can be down to 0.001. It was pronounced that each the molecule has a different role; however, due to mutual interaction, very low friction can be maintained even at very high contact pressures. Particularly, it was explained that HA is anchored to the surface of the cartilage via molecules of lubricin, creating a complex layer together with phospholipids, thus providing extremely low friction. The importance of so-called boundary layer and the interaction of molecules was recently highlighted by Jahn et al. [18]. The authors pointed out that better understanding of the mechanisms occurring inside the joint, ensuring operation under low level of friction, should be of a greater interest, since it may be an implication for many areas, including treatment of OA, preventing the necessity of joint replacements.

Considering the investigation of lubrication within hip replacements, it must be taken into account that ball-on-disc model configuration, which was employed several times in the above references, does not correspond to the real geometrical configuration of the joint, where the contact is highly conformal. The first step on the way to approach higher degree of conformity was conducted by Vrbka et al. [23] who substituted the glass disc by the convex glass lens, thus obtaining completely different results compared to previously investigated ball-on-disc arrangement [24]. Addressing the implication of the importance of contact geometry, we developed a simulator based on the principle of pendulum to be able to investigate the film thickness under real geometrical configuration [25]. Recently, our effort was focused on the clarification of the influence of head diameter, diametric clearance and head material on film formation; finding that thicker film is formed when