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Friction control of mechanical seals in a ventricular assist device

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Abstract

Low and stable friction is required for mechanical seals in implantable ventricular assist devices. In this study, a specialized test apparatus was designed to test the frictional properties of a mechanical seal in blood in implantable ventricular assist devices. It was shown that a blood-derived protein film forms on the sealing surfaces and causes higher and unstable friction than that in water. Further, it was shown that concave surface features on the substrate initially catch aggregated proteins that are denatured by friction, thus the protein film progresses from concave to flat regions on the substrate. On the basis of this protein film formation mechanism, the creation of a smooth, hydrophilic sealing surface was proposed to control friction and its effectiveness was validated.

Keywords: Mechanical seal; Blood; Friction; Protein adsorption; Ventricular assist device; Surface roughness

1. Introduction

Implantable ventricular assist devices (VADs), used as a temporary cure while awaiting heart transplantation [1], assist the human heart by pumping blood with a rotating impeller, driven by a motor within the VAD. Electrical power to drive the motor is supplied from a portable battery and controller unit [1] to enable patient mobility for quality of life. The mechanical seal in the VAD consists of seat and seal rings that support rotation of the impeller [2]. Therefore, friction forces generated at the surface of the mechanical seal must be minimized and stabilized to ensure a long battery life and drive stability in next-generation VAD.

It has been suggested that blood components penetrate between the sealing surfaces [3]. Blood contains blood cells and small plasma proteins [4], so static protein adsorption [5] can occur on the artificial substrate of sealing surfaces through hydrophobic interactions between protein molecules and the substrate [6] and between the protein molecules themselves [7]. Furthermore, the effects of factors such as the concentration [8] and denaturation [9,10] of proteins, temperature [11], pH [12] and wettability [13,14] on protein adsorption have been widely investigated, showing that adsorbed protein can affect frictional properties [15–18]. These findings clearly indicate that protein adsorption can occur on the sealing surface of mechanical seals and affect the performance of VAD.

The effect of surface roughness [19] on protein adsorption must be considered, because the sealing surfaces of mechanical seals in VAD are relatively rough, when compared with the smooth substrates usually used to investigate protein adsorption, as represented by polished sensors in a quartz crystal microbalance [20–22]. Therefore, from the practical view point of achieving effective mechanical sealing, a fundamental investigation into the frictional properties of mechanical seals must be performed using driving conditions similar to those present in a VAD to simulate an actual device. Furthermore, a sealing surface must be designed to realize low and stable coefficients of friction in blood, by controlling protein adsorption, based on fundamental investigations. However, until now, there has been no test apparatus available to investigate the frictional properties of the sealing surfaces in VAD, and to date there have been no fundamental investigations of their frictional properties in blood.

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This study describes the design of a specialized test apparatus for investigating the frictional properties of mechanical seals in blood and provides fundamental insights into the factors that affect those properties. Furthermore, a material design that improves the friction properties of mechanical seals in blood is proposed and validated.

2. Design of test apparatus and evaluation of the frictional properties of mechanical seals in blood

2.1. Test apparatus

To simulate the frictional forces generated at a mechanical sealing surface in an actual VAD, the structure of the test apparatus was designed based on the actual structure of a VAD [1]. The driving conditions, such as rotational frequency and load could thus simulate those in a VAD.

A schematic of the designed test apparatus is shown in Fig. 1. A seat ring was fixed on the base part of the apparatus, while the seal ring was rotated by a motor through a shaft with a magnetic coupling. The seat ring and rotating shaft were supported by a hydrodynamic bearing on the base part. Blood was held in a chamber surrounding the mechanical seal, while purified water was circulated inside the mechanical seal [23] by a roller pump system, thus simulating the driving conditions of a mechanical seal in an actual VAD.

To avoid frictional torque generated anywhere other than at the sealing surface and sliding bush, a magnet coupling was used to connect the rotational axis, covered by the circulation circuit and motor. A torque meter was mounted between the sealing surface and the motor driving the seal ring against the fixed seat ring. A controlled load was applied to the sealing surfaces through a pair of magnets mounted at the end of shafts inserted in the chamber, with the distance between the magnets controlled by an electric actuator. The friction coefficient was calculated using the following equation:

$$\mu = \frac{3T_f}{2W}\left(\frac{r_o^2 - r_i^2}{r_o^3 - r_i^3}\right) \quad (1)$$

where T_f, W, r_i and r_o represent the frictional torque, applied load, and the inner and outer radius of the sealing surface. The load and rotational frequency of the motor were fixed at 2 N and 2000 rpm, respectively, so that the driving conditions of VAD were simulated. Three hundred milliliters of purified water was circulated inside the mechanical seal, with a flow rate, gauge pressure and temperature of 185 ml/min, 15.9 kPa and 25 °C, respectively. Purified water and blood were used as test fluids. Blood was obtained from the left common carotid artery of a living goat (mature female, 23.5 kg) and kept in a blood bag (KARMI Blood Bag, Kawasumi Laboratories, Inc.) containing anticoagulant (citrate phosphate dextrose) to inhibit the coagulation driven by fibrinogen and platelets that could otherwise affect the measured frictional properties.

2.2. Specimen

A mechanical seal installed in a VAD was used as a specimen in this study. The mechanical seal consists of a seat ring (silicon carbide, SiC) and a seal ring (a carbon matrix impregnated with resin, C). Many concave features could be observed on the seat ring surface with approximate diameters and depths of up to 10 μm and 1.5 μm, respectively, while the height of protruding features was 500 nm, caused by aggregation of the impregnated resin. The arithmetic mean roughnesses of the entire seat and seal ring surfaces were 67.6 and 53.6 nm, respectively. The arithmetic mean roughness of the flat regions on the seat ring was 3.6 nm while that of the carbon matrix part of the seal ring was 16 nm, which was relatively rough because it had smaller asperities than the plateau region of the seat ring.

3. Experimental results

3.1. Frictional properties of the mechanical seal in blood

To evaluate frictional properties of the mechanical seal (SiC/C) installed in the VAD, the friction coefficient in water and blood were measured. The typical frictional properties measured in water and blood are shown in Fig. 2. The friction coefficient when using water showed around 0.5 immediately after starting the

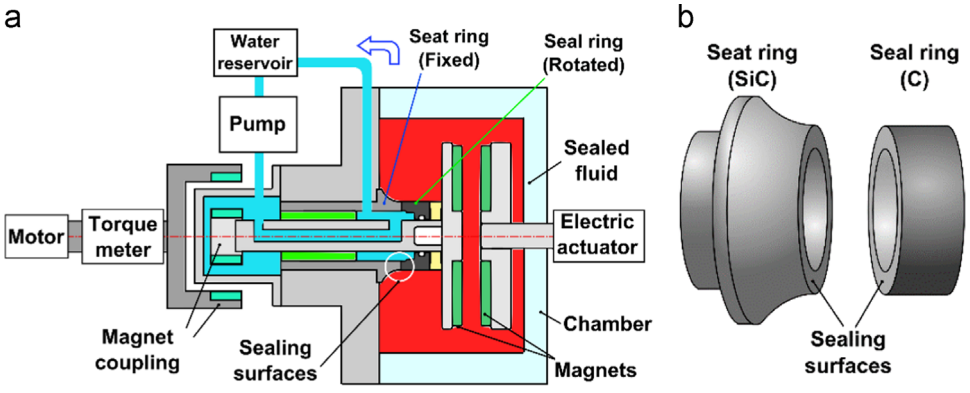

Fig. 1. (a) Schematic image and (b) detail of sealing surfaces of the experimental apparatus.