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Application of electrical resistance tomography for thrombus visualization in blood

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ABSTRACT

Visualization of a thrombus is very important in the development of various artificial organs and extracorporeal circulation devices. This paper presents an application of electrical resistance tomography (ERT) technique for the visualization of a thrombus in blood. Experiments were conducted in static and flowing bovine and swine blood samples. Artificially created thrombi were mixed in the blood samples for visualization. Eight-electrode tomography sensor was used for the measurement. Cross-sectional resistivity distribution was reconstructed using linear back projection algorithm. A thrombus was characterized by increased local resistivity. We successfully reconstructed the time, size and cross-sectional location of a thrombus, and reached a conclusion that the concentration and orientation of the RBCs in a thrombus contributed to the increase in the resistivity. The increment was relatively higher in the static blood than in flowing blood. These findings can be helpful in the development of an instrumentation system for the real-time monitoring of blood to visualize a thrombus. Developers of left ventricular assistance devices, heart-lung machines, hemodialyzer etc., and the end-users (i.e. patients) can greatly benefit from such a system.

1. Introduction

Cardiovascular diseases account for the one-third of the total deaths worldwide [1]. Similarly, majority of the patients with renal diseases regularly go for hemodialysis. The organ donation rate is still very low. These problems are currently being addressed through the development of artificial heart valves, implantable ventricular assistance devices (VAD), heart–lung machines, dialyzers and other artificial organs [2–4]. However, there are many challenges in the development and application of these devices. One of the major challenges is to control the thrombosis (i.e. formation of blood clots). From fluid dynamic perspective, thrombosis is induced by the low shear rate [5]. Similarly, when blood comes into contact with artificial surface a tendency to form thrombus is increased due to bio-incompatibility [6,7]. Developers pay a lot of attention for design optimization to reduce the risk of thrombogenicity with the help of numerical modeling and experimental analysis of shear rate distribution and secondary flow patterns [5,8–11]. Furthermore, in order to minimize the bio-incompatibility issues, the device components are either made from biocompatible materials or have surface covered with biocompatible coatings. The devices are evaluated using conventional thrombogenicity tests like activated clotting time (ACT) and thromboelastography. There are several limitations with these tests in terms of device evaluation. Firstly, the blood should be withdrawn regularly from the flow channel, which intervene the flow conditions. Secondly, a single measurement requires more than ten minutes. Thirdly, these methods give information of thrombogenicity at a particular time but cannot confirm whether thrombus was formed at that time. Therefore, there is a need of online blood flow monitoring technique that can give information of time, size and cross-sectional location of a thrombus in real time. This work is focussed on the development of such a monitoring system for the extracorporeal circulation devices.

In this context, Oshima et al. [12], and very recently Sakota et al. [13] evaluated optical techniques for blood flow monitoring to visualize a thrombus. However, biocompatible coatings, which block the optical passage, make the practical realization of such a technique difficult. An electrical technique can be an alternative in such a condition. The electrical properties of blood have

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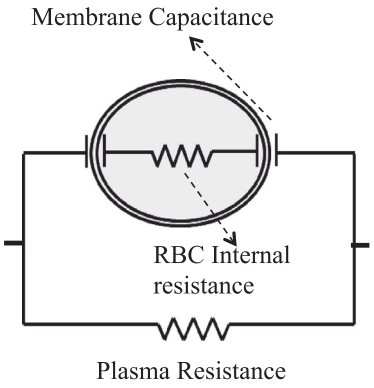

Fig. 1. Electrical representation of blood.

successfully been exploited in many biomedical applications [14–16] and have potential for use in thrombus visualization in blood in extracorporeal circulation. In terms of electric circuit diagram, the blood can be represented by three components as shown in Fig. 1. Blood plasma and intracellular space of the red blood cells (RBCs) are considered as resistive components while RBC membrane, which has significantly low conductivity, is treated as a capacitive component. Overall blood resistivity at the lower AC frequency is mathematically expressed as in Eq. (1). This mathematical expression is based on the Maxwell–Fricke formulation of electrical behavior of the suspension of ellipsoidal particles and is widely used in the analysis of biological cells and suspensions [16,17]:

$$\rho_b = \rho_p \frac{1 + kH}{1 - H} \tag{1}$$

In Eq. (1), ρ_b is the resistivity of the whole blood and ρ_p is the resistivity of the plasma. H is the concentration of RBCs in blood (commonly called as hematocrit) and k is a variable that depends upon geometry and orientations of RBCs.

Our working theory on thrombus visualization by electrical method is that the presence of thrombus results in the change in distribution of blood cells, which ultimately affects the local volume concentration of RBCs (i.e. H in the above equation) at the channel cross-section. Furthermore, the change in resistivity of plasma ρ_p is also expected due to the change in the concentration of coagulation factors. For example, earlier studies have shown important relationship between fibrinogen (a prominent coagulation factor) and electrical resistivity of blood [18,19]. Also, the orientation of RBCs in thrombus may be different from freely moving RBCs in blood which influences the factor k in Eq. (1). In a study, Hoetnik et al. [17] reported that the resistivity is higher if RBCs are randomly aligned with respect to an electric field. Thus, spatio-temporal visualization of the resistivity change in the blood,

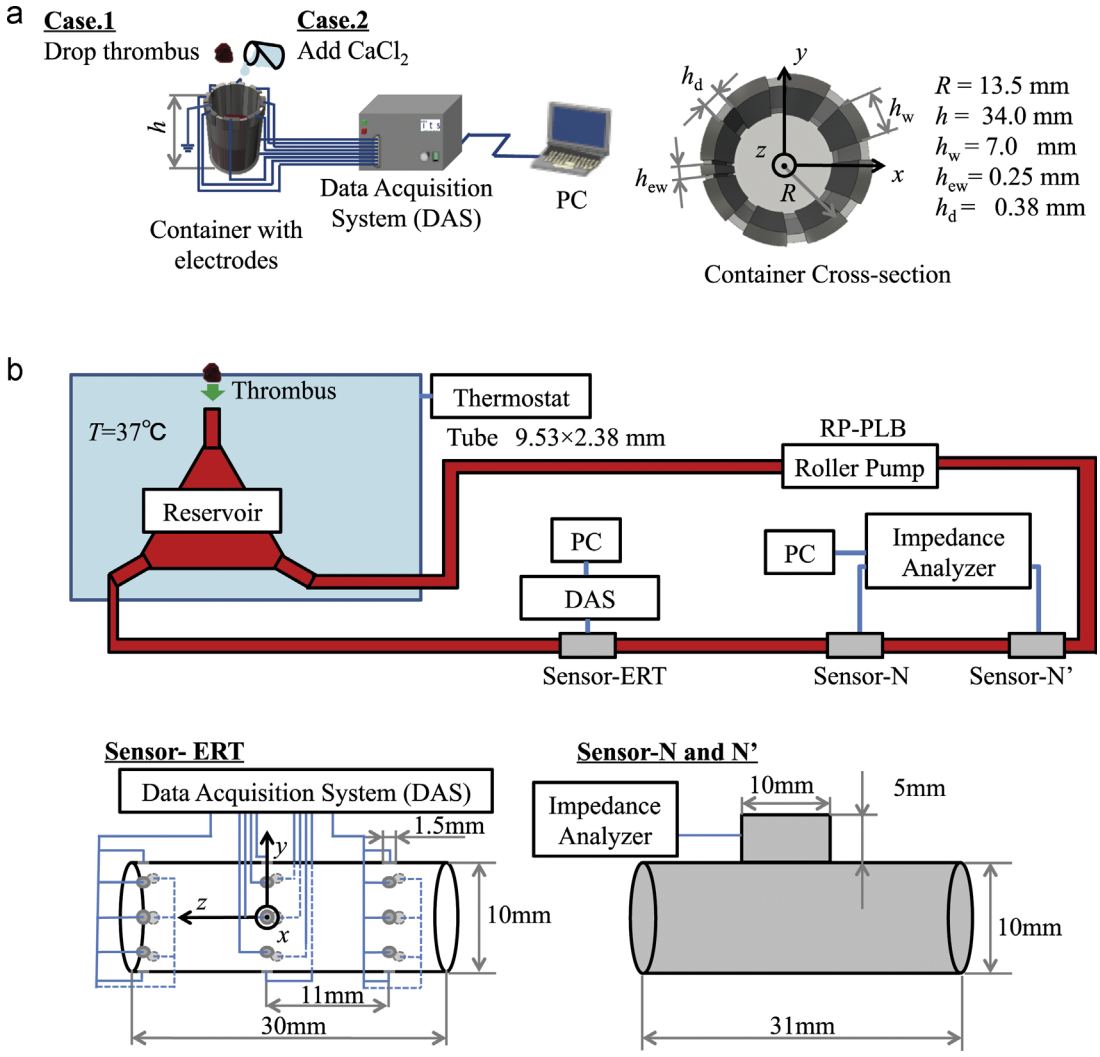

Fig. 2. Experimental setup under (a) static conditions and (b) flowing conditions.