VISUALIZATION OF THROMBOGENIC PROCESS IN ARTIFICIAL HEART USING ELECTRICAL RESISTANCE TOMOGRAPHY

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Visualization method(s): tomography
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ABSTRACT: Many of the heart patients are benefitted with the emergence of prosthetic devices like ventricular assist device (VAD) and the total artificial heart (TAH). Naturally, when blood comes in contact with artificial systems it tends to clot more. Hence, blood clotting is the major issue in these devices. That is why the patients take regular medicine. The frequent use of such a medicine results to other consequences. Due to this, the optimum use of medicine is desirable. To address this issue, we have made an assessment of instrumentation systems based on electrical resistance measurement which can monitor the blood and detect the thrombogenic activities in the early stage. The experimental results obtained by monitoring the bovine blood under thrombogenic conditions are presented.

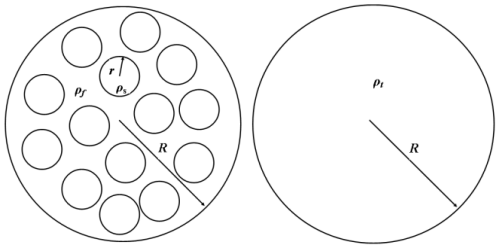
1. INTRODUCTION

Ventricular assist devices and artificial hearts are developed for the purposes of assisting and substituting for diseased cardiac functions. The emergence of implantable artificial hearts has brought a better quality of life to heart patients, and has allowed them to leave the hospitals and return to their homes [1-7]. When blood comes in contact with foreign surface, unlike the natural system of the body, it tends to clot more than normal due to incompatibility [8-10]. The designers of artificial heart pumps have paid maximum attention to minimize the compatibility problem due to design artifacts. Two of the present authors also presented the importance of flow visualization technique to deal the issue in the design stage [3, 6]. In spite of these efforts, there is always a risk of thrombosis formation. Due to this, regular anticoagulation medication is inevitable for artificial heart patients. But, consistent use of anticoagulants can be dangerous too. For example, it can cause increased bleeding after injury. The patients would be greatly benefited if monitoring system of blood could be developed which could analyze the risk of impending thrombosis, and can assist them to determine the appropriate timing for the consumption of anticoagulant medicine.

In the present work, authors have proposed the use of electrical properties of the blood to visualize the risk of impending thrombosis. Measurement systems using the electrical properties of living tissues are used in many biological applications [11-13], and thus have the potential to reveal the important clinical properties in relation to risk of thrombosis. The theoretical basis for the work is described in Section 2. In section 3, we have presented the experimental assessments. The paper is concluded in section 4.

2. ELECTRICAL PROPERTIES OF THE BLOOD AND THROMBOSIS

Blood can be considered as the conductive spherical bodies (blood-cells) floating in conductive liquid medium (plasma).Hence, the basic philosophy behind the electrical modelling of the blood goes to the work published by J. C. Maxwell in 1873 where the equivalent resistivity of the conductive spherical cells disseminated in the conductive fluid was formulated [14]. According to the formulation, if N spheres each with radius r and resistivity ρ_s are disseminated in the fluid with resistivity ρ_f as shown in Figure 1 (a), then they can be equivalently represented by a single sphere of radius R with resistivity ρ_t as shown in figure 1(b), where ρ_t is expressed mathematically as shown in equation (1).



(a) (b)

Fig. 1 (a) *N* spheres having with radius *r* and resistivity ρ_s disseminated in the fluid with resistivity ρ_f and enclosed in the sphere of Radius *R*. (b) One sphere of Radius *R* electrically equivalent to the system of the spheres in (a)

$$\rho_t = \rho_f \frac{(1-V_{con})\rho_f + (2+V_{con})\rho_s}{(1+2V_{con})\rho_f + 2(1-V_{con})\rho_s} \qquad (1)$$

In equation (1), V_{con}, as expressed in equation (2), is the volume concentration of the spheres each with radius *r* in the sphere of radius *R*.

$$V_{con} = \frac{N \times \frac{4}{3}\pi r^3}{\frac{4}{3}\pi R^3} \qquad (2)$$

The mentioned philosophy has been widely used in biophysics studies where any human tissue is considered as the suspension of cells [11-13]. Visualization methods, such as electrical resistance tomography and electrical capacitance tomography, are being successfully used in the analysis of solid-liquid two phase flows [15,16], and have potential to be applied in the visualization of the thrombogenic process in the artificial heart systems.

From the above equations, it can be seen that the equivalent conductivity depends upon the concentration and conductivity of the spheres (blood cells in the case of blood) and conductivity of fluid (plasma in the case of blood). For devising an appropriate system for the visualization of thrombogenic process, it is necessary to start from the general concept of thrombus formation. Rudolf Virchow (1821- 1902) described the factors contributing to venous thrombosis in 1856 which is famously called as Virchow's triad [15, 16]. The components of the triad are: (i) Alterations in blood flow (ii) Vascular endothelial injury (iii) Alterations in the constitution of the blood. Though Virchow originally referred to venous thrombosis, the concept can also be applied, in general, to any thrombosis. The third one is the basis of our present work considering the first two are addressed in the design stage. There are various constituents of the blood but soluble coagulation factors are very important. It is believed that the change in plasma proteins contribute to the change in electrical properties of the blood. In present work, we have considered that the concentration change of coagulation factors contribute to the change in resistivity of the blood. So far as the electrical response of thrombogenic process is concerned, it is expected that the change in concentration of the the coagulation factors contribute to the change in electrical resistivity of the plasma, and ultimately the resistivity of the whole blood.

3. EXPERIMENTS AND RESULTS

Two experiments have been conducted to study the electrical response of the blood during the thromogenic process. In the first experiment (experimental setup shown in Figure 2), 500 ml of Bovine blood was circulated with the help of centrifugal blood pump (BPX-80 Bio-Pump) at the rate of 5 L/min for 155 minutes. The reservoir was kept in the water whose temperature was maintained at 37^{o}C. The electrical resistance was measured using a precision impedance analyser (Agilent 4294A). The measurements were taken at 100kHz frequency with the alternating current voltage of 500mV.

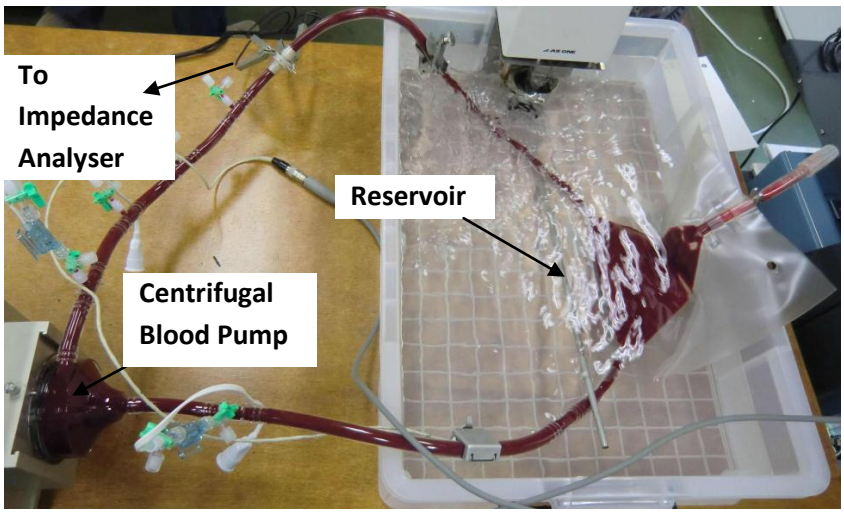


Figure 2. Experimental setup to observe the change in electrical resistance of blood in thrombosis-prone situation

The blood was supplied with calcium chloride regularly by observing the activated clotting time (ACT) so as to make it vulnerable to thrombosis. Figure 3 shows the change in resistance over time. If compared, with the ACT readings shown in Figure 4, the rapid rise in resistivity of the blood was observed when the ACT was below 200 seconds. The value of ACT of less than 200s to the similar in-vitro experiment shown comparatively higher risk of thrombosis as reported in Maruyama et al. [10]. This shows the possibility that the risk of thrombosis can be represented by the change in resistance.

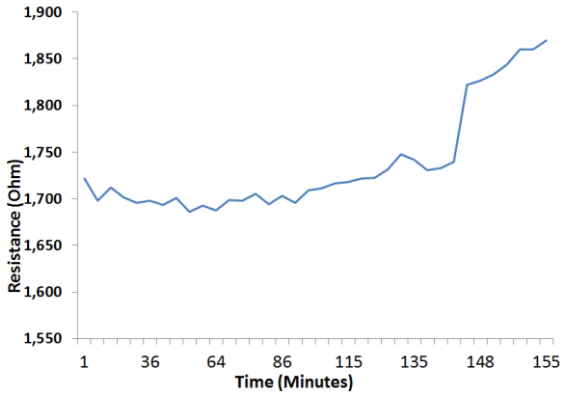


Figure 3. Change in electrical resistance of blood during experiment

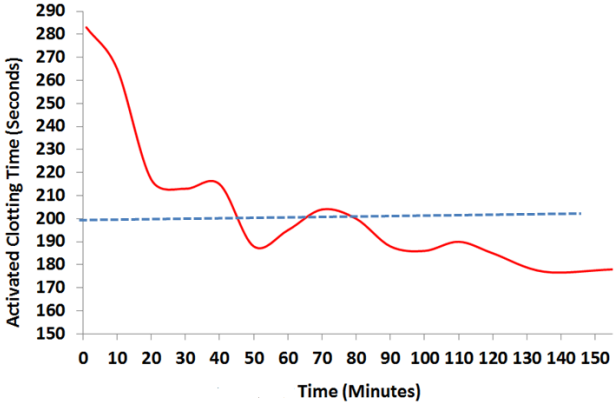


Figure 4. Activated clotting time (ACT) of blood during experiment

The second experiment was carried out to study the possibility of electrical resistance tomography (ERT) method to reflect the change in cross-sectional resistivity. As shown in Figure 5, the acrylyic container which doubles as a tomographic sensor was filled with bovine blood. The 16 electrodes were connected to ITS-2000 data acquisition system (Industrial tomography systems plc, UK) and tomographic reconstruction was carried out using Sensitivity back-projection algorithm. The reconstructed tomogram shown in Figure 6(a) represents the condition when there was no

change in pattern of tomogram for long time (stable tomogram). Figure 6(b) and 6(c) represent the scenario when thrombogenetic process was activated with the use of calcium chloride solution. The pattern which shows higher resistivity in the central area and lower resistivity away from the centre (shown in Figure 6(a)) is no more preserved after the addition of calcium chloride indicating the thrombogenic process (i.e. in the region represented by higher resistivity even away from the centre).

Though these are the preliminary assessments of the Electrical resistance change due to thromogenic activity in the blood, the results are positive enough to encourage the further experiments.

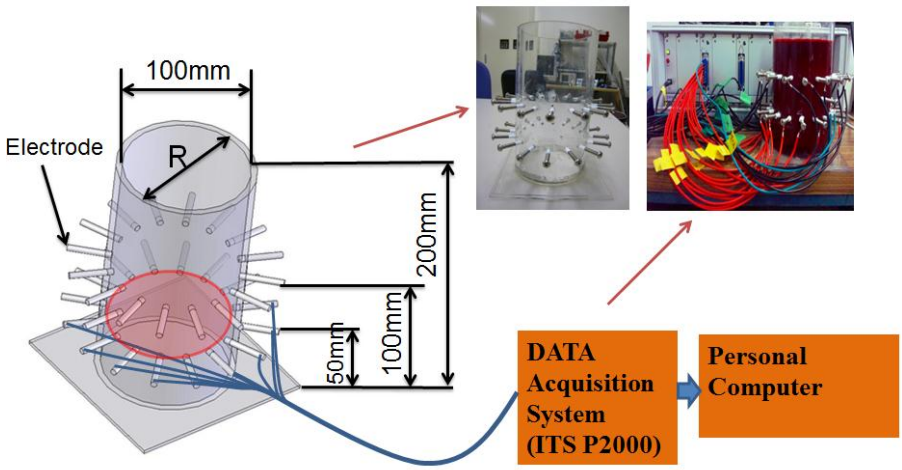
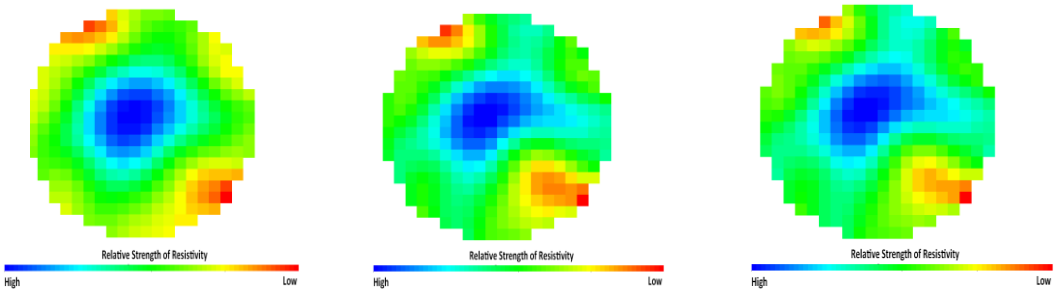


Figure 5. Experimental setup for electrical resistance tomography



(a) (b) (c)

Figure 6. Electrical resistance tomograms of a tube containing bovine blood a) before activating the clot b)5 minutes after activating the clot c) 10 minutes after activating the clot

4. CONCLUSIONS

The use of electrical properties of the blood has been studied to visualize the thromogenic process of blood. In on experiment, in-vitro live monitoring of blood was performed where change in resistance was observed with the increased risk of the thrombosis. In another experiment, the resistivity distribution was observed using electrical resistance tomography which showed the remarkable change before and after the clot activation. This is the first step towards the visualization of thrombogenic process in artificial heart system. Thorough investigation considering fluid-dynamic, biochemical and biophysical scenario of thrombosis formation will be carried out in the near future.

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