Gaussian distribution of relaxation through human blood

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ABSTRACT

The complicated structure of human blood has been characterized based on relaxation time, τ, and the Cole–Cole parameter, α, obtained from dielectric measurements. As previously reported by different authors, the experimental data show net deviation from the classical Debye model with certain distribution of relaxation times (D_τ). Plots of α versus width of the relaxation rate distribution of micro-particles inside the blood show that D_τ drastically affects the dielectric properties of the fluid. The mathematical function of D_τ is found to be Gaussian and we find that the α values of normal blood have net lower magnitude than that of diabetic blood. These results suggest that glucose in blood increases the broadness of the parameter α, which have significant importance in diabetic-biosensor manufacture.

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1. Introduction

Recently [1], measuring the complex permittivity in blood and human tissue in general has become a common practice with several clinical applications. For example, different applications based on bioimpedance use the technique of fitting the measured complex permittivity data to a model described by the Cole equation and estimating the Cole parameter [2] in skin tumor (cancer) detection [3], respiration monitoring, determined cardiac stroke volume, and cardiac output by means of impedance cardiography [22] and assessment of body composition [4]. Although the complex permittivity, ε^*, of human blood has been long studied, some important questions still remain to be answered. One of those is: how does the distribution of different micro-particles (MPs) through the blood affect the physical behavior of ε^*? What is the mathematical shape of this distribution? For example, in order to characterize the distribution of red blood cells (RBCs), white blood cells (WBCs), micro-light blood particles (MLPs, which are lighter than RBCs and WBCs), and other micro-particles, dielectric measurements are considered as one of the most effective methods. In reality the dielectric relaxation process of normal and diabetic blood has been observed since early times [5–8]. This relaxation process is described to be almost Debye-type [9], i.e., the Cole–Cole parameter α [10] is unity or slightly smaller than unity, and it has been reported that the relaxation time of water molecules, α_{water}, is found to be about 8.27×10^{-12} s at 25 °C [11]. The relaxation time, τ, of micro-particles in human blood

obtained by dielectric measurements is defined as the periodic oscillation time of a micro-particle suspended in the serum. However, several hundreds of millions of these MPs are distributed through the serum within a few drops of the human blood. Each micro-particle has its own mass and hence its own inertia. When these MPs are subjected to an AC electric field, they form dipoles that oscillate with the frequency of the external field. The inertia distribution results in different relaxation rate distributions (D_τ) throughout the polarized liquid. As the fluid becomes more inhomogeneous, the width of D_τ increases.

The relaxation process due to free RBCs, WBCs, and MLPs is generally expressed by the Cole–Cole equation, where the relaxation curve is broader than that of the Debye-type.

The relaxation strength, $\Delta\varepsilon = \varepsilon_{\text{DC}} - \varepsilon_\infty$, τ, and the parameter for the shape of relaxation curve, α, are dependent on the distribution of different charges throughout the polarized liquid [10].

Fricke and Morse (FM) [12] are the pioneers who successfully developed models for the electrical and dielectric properties of living tissues, which can be applied to the human blood. One of these models describes the Debye relaxation process, which is characterized by only a single characteristic time constant and thus, corresponds to a single dispersion. Since 1925, the FM model has been widely used and after many decades some authors are still using it [13,23]. This is because it can simply describe qualitatively the dispersion in the α dispersion region as defined by Schwan [14] in 1957 (α dispersion is not to be confused with the Cole parameter α under investigation here; the same notation is kept for convenience). However, since the first studies of the FM model, scientists have observed that this capacitive FM model is not accurate enough to fit experimental results in fluid-suspension studies of, for example, the human blood [10]. Moreover, calculations using the

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