



Rheological properties of human blood in the network of non-equilibrium thermodynamic with internal variables by means of ultrasound wave perturbation



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ABSTRACT

This study is focused on the responses of whole blood and erythrocytes in saline solution when subjected to elastic stresses induced by ultrasound wave. Using a theoretical approach we obtained the expression of some thermodynamic functions depending on the complex wave number. This allows to the determination of very important rheological properties of the aforementioned materials and the explanation of how they react to frequency dependent ultrasound perturbation. We noted that the stress is greater in the solution of erythrocytes compared to whole blood but this difference is reduced as we approach to 10^8 Hz. These observations, in red blood cells solution might be due to lack of "oncotic protection" exerted by plasma proteins (albumin, ceruloplasmin) but when the frequency increases the same proteins precipitate because they lose their native folding resulting in the increase of whole blood viscosity. We could define 6.10^7 Hz as the threshold value beyond which in whole blood the ultrasonic waves cause the triggering of the phenomenon and the plasmatic proteins as a sort of "lubricant agents" that protect erythrocytes by the environmental perturbations. This work represents a preliminary part of wider results that we would like to achieve to the purpose of determining the threshold values of the macromolecular stability of a particular tissue as the human blood in response to dynamic stress.

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1. Introduction

The study of the rheological properties of biological materials plays an increasingly important role in understanding the structure and evolution of living matter. In particular it may serve for a comparative study of physiological and pathological tissues. Being open systems, tissues give rise to phenomena that can be studied only by applying the non-equilibrium thermodynamics [1–9].

There are in the literature different ways to approach the study of irreversible phenomena but in what follows we will refer to the thermodynamics with internal variables formulated by Kluitenberg [4–7]. It follows from the theory that several types of (macroscopic) stress fields may occur in a medium: a stress field $\tau_{ik}^{(eq)}$ which is of a thermo-elastic nature, a stress field $\tau_{ik}^{(vi)}$ which is analogous to the viscous stresses in ordinary fluids, and stress fields $\tau_{ik}^{(1)}$ which are probably connected with the microscopic stress fields surrounding imperfections in the medium. The stress field $\tau_{ik}^{(eq)} + \tau_{ik}^{(vi)}$ is the mechanical stress field which occurs in the equations of motion and in the first law of thermodynamics. In this formulation special functions describing phenomena that other theories

do not consider are introduced. For example when studying rheological phenomena it is generally introduced a quantity that represents the state of internal deformation and which commonly is represented by a double symmetrical terms: the strain tensor. In Kluitenberg's theory this is split into two components with a specific kinematic meaning related to elasticity and inelasticity. This leads to the introduction of new dynamic functions that do not appear in other theories and that are related to specific phenomena. This is as though looking the matter with a magnifying glass that lets you see particular phenomena that are not classically considered. In other words the approach by us developed leads to a more detailed description because it is able to disjoin phenomena that by experimental techniques cannot be measured directly. In fact generally, a rheological measure consists in the evaluation of two parameters related to dissipative (loss module) and non dissipative (storage module) processes but it is not specified the nature of dissipation: inelastic, viscous...

Our approach is able to evaluate the species of dissipation mechanical [10–14] and dielectric [15–21]. There are several experimental techniques to measure rheological properties of tissues, the simplest applicability of which depends on the consistence of tissues to investigate. So for example, in bone tissues we can use shear or tension dynamic techniques, while these techniques result very difficult to apply to soft tissues because it is difficult to couple the probe to the material. And it is

Abbreviations: RBCs, red blood cells.

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more difficult to apply this to liquid tissues (even it is possible). If one consider liquid tissues as the blood, another technique results easy to apply: the ultrasound one [20,22–25]. In fact this technique consist of an ultrasound perturbation applied to the fluid and to the measurement of attenuation and velocity of the wave as function of the frequency. Obviously, this is not invasive and it is easy enough to be applied even to in vivo tissues [24–26]. The question now is to extract rheological information from this measure. Although exists well known relation between the measured attenuation, velocity and stress function these are not enough for specify the nature of dissipation processes as aforementioned. We have developed a theory that leads to the determination of functions related to the nature of the dissipation. In a previous paper [26] we have considered red blood cells (RBCs) in saline solution and whole blood subjected to an ultrasound wave perturbation as function of the frequency and we have determined state and phenomenological coefficients by means of which an expression of the entropy production has been obtained. Here we will extend the previous paper by determining some thermo-mechanical functions (stress) and kinematical ones (strain) as function of the ultrasound frequency dependent wave vector. This leads to a better understanding of some processes which occur inside RBCs solution.

2. Material and methods

To understand the importance of the function introduced in the theory we will analyze the meaning of them and how they are introduced without specifying the mathematical formalism. We start by considering the strain tensor:

If we indicate with u_i ($i = 1, 2, 3$) the displacement vector of a point P with respect to the position of P at a time t_0 the total symmetric strain term is defined as [1,2]:

$$\varepsilon_{ik} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_k} + \frac{\partial u_k}{\partial x_i} \right) \quad (1)$$

$(i, k = 1, 2, 3)$

The diagonal components ε_{11} , ε_{22} , ε_{33} give the relative elongation (contraction) along the coordinate axes while non diagonal elements describe the shear strain and the trace is the relative increase of volume. Here it is assumed that the deformations are small and occur to a constant temperature T . Therefore the tensor Eq. (1) gives the state of deformation of the medium in the surrounding of P. This represents the total deformation irrespective by its nature. It is well known that generally by a thermo-mechanical point of view, only two types of deformation are considered: elastic and inelastic which are admitted in the network of not dissipative and dissipative phenomena respectively. So the elastic deformation is recovered instantaneously while inelastic one can be divided into anelastic and plastic deformation. Anelastic deformation is recovered provided that one waits long enough, while plastic deformation is not recovered. In what follows we neglect plastic phenomena and consider only elastic and anelastic deformation. The first is reversible and is not accompanied by dissipation; the second is irreversible and dissipative (in agreement with Plank's point of view).

Indeed we observe that in nature no reversible phenomena occur, so the elastic deformation does not exist. The elastic property of a medium is only an approximation which can be considered good depending on the time recover of the deformation. As smaller is this time as more elastic is the medium. In the theory, we will consider (Kluitenberg's thermodynamic of irreversible processes with internal variables) the irreversibility of a phenomena is related to the entropy production: if a quantity does not contribute to the entropy production the phenomenon to it associated is reversible.

For a detailed description of this theory we remand to bibliography [3–7]. Here we will remark synthetically some aspects of the theory which justify our approach. It can be show [3–7] that under particular conditions the total strain tensor can be splitted in two parts the change

of which contribute to the entropy production and therefore they describe two irreversible phenomena. We indicate with $\varepsilon_{ik}^{(0)}$ the part of the strain tensor that does not appear in the entropy production and therefore it is the reversible part of the total strain if no viscous phenomena occur in the medium; we call it “elastic strain tensor” (but we remember that generally $\varepsilon_{ik}^{(0)}$ appear in the entropy production). The second part of the total strain can be considered [7] as the contribution of n microscopic phenomena and therefore it is needed to consider a strain term for every phenomena so we indicate them with $\varepsilon_{ik}^{(\alpha)}$ ($\alpha = 1, 2, \dots, n$).

The change of these tensors appears in the entropy production and therefore they reflect irreversible phenomena. Thus we have

$$\varepsilon_{ik} = \varepsilon_{ik}^{(0)} + \varepsilon_{ik}^{(1)} + \varepsilon_{ik}^{(2)} + \dots + \varepsilon_{ik}^{(n)} \quad (2)$$

In our purpose it is enough to consider only one microscopic phenomenon, $n = 1$, so to obtain

$$\varepsilon_{ik} = \varepsilon_{ik}^{(0)} + \varepsilon_{ik}^{(1)} \quad (3)$$

We remark that $\varepsilon_{ik}^{(0)}$ and $\varepsilon_{ik}^{(1)}$ describe two different microscopic phenomena and so they can be considered independent. Therefore in the entropy representation one can consider the specific entropy s as function of specific internal energy u , of $\varepsilon_{ik}^{(0)}$ and $\varepsilon_{ik}^{(1)}$:

$$s = s(u | \varepsilon_{ik}^{(0)} | \varepsilon_{ik}^{(1)}) \quad (4)$$

Or by taking into account the relation (3), one has:

$$s = s(u | \varepsilon_{ik} | \varepsilon_{ik}^{(1)}) \quad (5)$$

In this last equation $\varepsilon_{ik}^{(1)}$ is an additional tensorial variable which is used to describe the state of the medium (it is useful remember that in classical thermodynamic theory $\varepsilon_{ik}^{(1)}$ does not appear in specific entropy, and one has $s = s(u | \varepsilon_{ik})$).

Such additional variables, on which the entropy depends and on which the substantial time derivative does not appear in the first law, may be called internal thermodynamic variables.

From Eq. (5) it follows that the temperature T is [5–7]:

$$\frac{1}{T} = \frac{\partial s(u | \varepsilon_{ik} | \varepsilon_{ik}^{(1)})}{\partial u} \quad (6)$$

Moreover it is defined the equilibrium stress tensor $\tau_{ik}^{(eq)}$ by [5–7]:

$$\tau_{ik}^{(eq)} = -T\rho \frac{\partial s(u | \varepsilon_{ik} | \varepsilon_{ik}^{(1)})}{\varepsilon_{ik}} \quad (7)$$

and the affinity stress tensor $\tau_{ik}^{(1)}$ conjugate to $\varepsilon_{ik}^{(1)}$ by [5–7]:

$$\tau_{ik}^{(1)} = T\rho \frac{\partial s(u | \varepsilon_{ik} | \varepsilon_{ik}^{(1)})}{\partial \varepsilon_{ik}^{(1)}} \quad (8)$$

where ρ is the mass density (mass per unit of volume). If τ_{ik} is the stress tensor which appears in the indefinite equations we can introduce the viscous stress tensor $\tau_{ik}^{(vi)}$ as:

$$\tau_{ik}^{(vi)} = \tau_{ik} - \tau_{ik}^{(eq)} \quad (9)$$

Moreover it can be shown [7] that under certain conditions the following state and phenomenological equations can be written:

$$\tau^{(eq)} = b^{(0,0)} \varepsilon^{(0)} \quad (10)$$

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