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The bulk modulus of solvated elastin

The great flexibility of rubber is due to the development of large shear strains at stresses so low that volumetric strains are insignificant. It is in this sense that the term incompressible is frequently applied to rubbers. In the discussion of the mode of deformation of elastin in tissues, in particular the aorta, it has been assumed that elastin deforms as a rubber with insignificant volumetric strain [1, 2]. There is, however, powerful evidence both theoretical and experimental which contradicts this apparently reasonable view. Elastin is deformed in the body in the diluted state. If a diluted rubber is deformed in the presence of diluent then the bulk modulus is extremely low. That elastin immersed in diluent does increase in volume when stressed under tensile load is in accord with a correct interpretation [3, 4] of the thermomechanical experiments of Weiss-Fogh and Anderson [5].

The reason for the difference between the bulk modulus of dry and diluted rubber is as follows. In the dry case, the volume can comply with the hydrostatic stress only by moving polymer molecules on average closer (or further) apart. The forces opposing this are extremely high which leads to negligible volumetric strains. However, if the rubber contains diluent and is immersed in diluent then it may comply with an imposed hydrostatic tension by absorbing (or desorbing) diluent. For example, when natural rubber is swollen with petroleum ether and is then stretched while immersed in petroleum ether from 150% of its initial unstretched length to 250% the swollen volume increases by 17% [6]. The essential difference between dry and swollen rubbers is well documented [7–9].

From this premise it follows that an elastin fibre subjected to hydrostatic tension in a diluent will exhibit appreciable volumetric strain. The relaxation time for the attainment of volume equilibrium after the imposition of a hydrostatic tension will depend on the permeability of diluent in elastin and on the thickness of the fibre. If the hydrostatic stress is oscillatory then diluent will pass in and out of the elastin at a rate which will depend on the relative magnitude of the volumetric relaxation time and the period of the imposed oscillation. An elastin fibre, according to our hypothesis, will act as a sponge accepting and rejecting diluent from neighbouring tissues when acted upon by an oscillatory hydrostatic tension.

It seems likely that the bulk modulus of smooth muscle deformed in the presence of diluent will also be low. In this case the stress-induced diffusion process across an elastin–smooth muscle composite layer will depend on the mechanical properties of the two components, and on their geometry and spatial arrangement. The stress-induced chemical flux generated along a concentration gradient by an oscillatory stress may well be considerably larger than the flux due to normal diffusion processes [10].

What then of the evidence [1, 2] supporting the assumption of incompressibility? It must be stated firmly that in view of the quoted evidence on diluted elastomers [3, 4, 6–9] any observation supporting incompressibility must be considered anomalous. For instance, in the experiments of Lawton [11] no volume increase was observed when a strip of canine aorta was stretched immersed in saline solution. This experiment may be rejected since the dilatometer used by Lawton measured the aggregate volume of both the aortic strip and the saline reservoir in which it was immersed. Any increase in volume of the strip would be caused by saline passing into the strip from the reservoir. The observed change in volume would, therefore, be zero whether the strip increased in volume on stretching or not [12].

The consequence of our hypothesis on, for instance, the opposed models for elastin (globular model [5] or random chain model [3, 4]), the nature of the diffusion processes in the aortic wall and the strain analysis around aortic bifurcations (with particular relevance to atherosclerosis), are the subject of continuing research.

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Comment on "The compression yield behaviour of polymethyl methacrylate over a wide range of temperatures and strain-rates"

The relationship between the yield stress in either compression (σ_c) or tension (σ_T) and log strain-rate ($\dot{\epsilon}$) has been shown by Duckett *et al.* [1] and Bauwens-Crowet [2] to have a definite curvature when a sufficient range of strain-rate is considered. This curvature was ascribed [2] to the possibility that at high strain-rates or low temperatures a second co-operative yield process begins to dissipate significant energy. Thus the deviation from linearity arises from the addition of two stress components, the first arising from processes which operate under all conditions and the second from a process which is only significant under conditions of low temperature or high strain rate and which was associated with the β mechanical relaxation. The object of this communication is to suggest that it may not be necessary to invoke two processes to explain the observed curvature.

A number of workers, including Haward and Thackray [3] have suggested that in order to account for the observed recovery of a polymer before and after yield it is necessary to consider that some of the applied stress is borne by an elastic recovery element and that this reduces the effective stresses on the time dependent flow process. In fact such an approach has been used by Bauwens-Crowet [2] to represent the β relaxation process. It is suggested that the effective shear stress τ^* may, therefore, be described as

$$\tau^* = \tau_a - \tau_r \qquad (1)$$

where τ_a is the applied stress and τ_r the stress borne by the elastic recovery process, i.e. the recovery stress. The effect of allowing for this extra stress term will be to cause a vertical shift to the curves of τ_a (or τ_a/T, where T is the absolute temperature).

It has also been noted [3] that a co-operative movement of a number of polymer segments would be necessary to permit significant flow in a solid amorphous polymer. If it is necessary for n such segments to move co-operatively during the yield process then it is possible to derive an expression for the rate at which such co-operative movement can take place in terms of the energy distribution statistics of the individual segments.

Following previous workers [2] the activation energy barrier for viscous flow for an individual polymer segment is put equal to Q. The probability p that a given segment occupies an energy level Q above its zero energy state is

$$p_1 = p_0 \exp(-Q/kT) \sinh(\tau^* v^*/2kT) \qquad (2)$$