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Nonlinear compressive mechanics of fibrin networks

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Fibrin is an insoluble polymer, the product of conversion of soluble plasma protein fibrinogen in response to damage of the vascular system. Fibrin forms a porous network of branching fibers that provides the scaffold of protective hemostatic blood clots and pathological obstructive thrombi. The structure and properties of the fibrin, including mechanical response to stresses generated by blood flow and during clot contraction, determine the course of pathological conditions, including bleeding, ischemic stroke or coronary heart disease. Using precise dynamic microscopic and rheological measurements we have suggested a model for the fibrin network compression behavior based on the theory of foams. The compression stress-strain curve was measured in experiment along with the loss and storage moduli at various strains with simultaneous confocal microscopy of the fibrin network during the deformation. Our results indicated a tri-phasic mechanical response of the network to compression[1]. In addition to the non-linear behavior of storage and loss moduli, we were able to reveal the non-uniformity of the compressive deformation with formation of a "compression front" or "phase boundary" along the direction of compression[1]. We described how the non-linear rheological behavior could be explained by viewing the fibrin network as a "cellular" solid that could exist in two phases: the low-strain phase in which the fibers are mostly straight, and a high-strain phase in which the fibers are mostly buckled. In displacement-controlled experiments such a solid has a stress plateau when there is a mixture of both phases. The fraction of each phase at equilibrium is determined by a lever rule. In the experiments, the storage and loss moduli at various degrees of compression of the fibrin networks were obtained by performing small oscillations around a certain strain. These oscillations changed the fractions of the two phases but they were not necessarily quasi-static. We described these two phases using a continuum theory of phase transitions in which a kinetic equation relates the rate of change of the fraction of the phases to the stress. Hence, we explained the storage and loss moduli of the networks while accounting for the contributions of the moving phase boundary as well as the viscoelasticity of each phase.

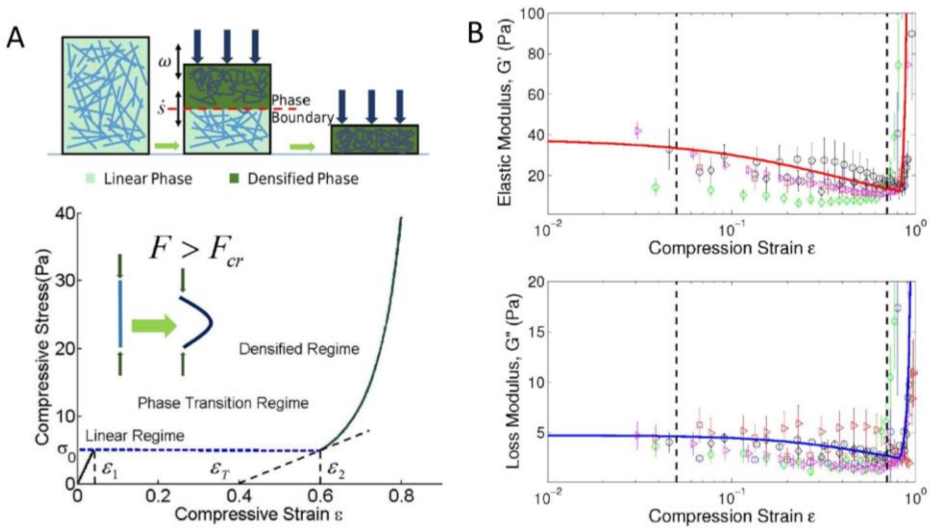

Fig. 1. A) A fiber network under compression: schematics of low strain phase on the left, high strain phase on the right and a mixture of the two phases in the middle. The bottom panel qualitatively shows a tri-phasic-behavior of the material with strain. B) Changes in shear elastic and loss moduli with compression. Symbols show experimental data and solid lines are the theoretical curves.

References

1. *Kim, O.V., Liang, X., Litvinov, R.I., Weisel, J.W., Alber, M.S. and Purohit, P.K.* Foam-like compression behavior of fibrin networks // Biomechanics and modeling in mechanobiology, 2016, V 15, pp.213-228.