

Universal Behavior of the Osmotically Compressed Cell and its Analogy to the Colloidal Glass Transition

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Mechanical robustness of the cell under different modes of stress and deformation is essential to its survival and function. Under tension, mechanical rigidity is provided by the cytoskeletal network; with increasing stress, this network stiffens, providing increased resistance to deformation. However, a cell must also resist compression, which will inevitably occur whenever cell volume is decreased during such biologically important processes as anhydrobiosis and apoptosis. Under compression, individual filaments can buckle, thereby reducing the stiffness and weakening the cytoskeletal network. However, the intracellular space is crowded with macromolecules and organelles which can resist compression. A simple picture describing their behavior is that of colloidal particles; colloids exhibit a sharp increase in viscosity with increasing volume fraction, ultimately undergoing a glass transition and becoming a solid. We investigate the consequences of these two competing effects and show that as a cell is compressed by hyperosmotic stress it becomes progressively more rigid. Although this stiffening behavior is dependent somewhat upon cell type, starting conditions, molecular motors, and cytoskeletal contributions, its dependence upon solid volume fraction is exponential in every instance. This universal behavior suggests that compression-induced weakening of the network is overwhelmed by crowding-induced stiffening of the cytoplasm. We also show that compression dramatically slows intracellular relaxation processes. The increase in stiffness, combined with the slowing of relaxation processes, is reminiscent of a glass transition of colloidal suspensions, but only when comprised of deformable particles. Our work provides a means to probe the cytoplasm under compression, and leads to results that are universal across cell type.