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IS CELL RHEOLOGY GOVERNED BY A GLASS TRANSITION?

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Mechanical stresses and resulting deformations play central roles in cell contraction, spreading, crawling, invasion, wound healing and division, and have been implicated in regulation of protein and DNA synthesis and apoptosis [1]. Current descriptions view cell mechanics as an interaction of numerous but distinct elastic and viscous elements expressing a broad but limited range of characteristic relaxation times [2, 3], with elasticity often thought to be regulated through a sol-gel transition [4, 5].

Here we report the development of a rheometry system that uses optical tracking of ligand-coated, magnetically twisted ferrimagnetic beads that are bound to integrin receptors on adherent cells (human airway smooth muscle cells, human bronchial epithelial cells, F9 mouse embryonic carcinoma cells, J774A.1 mouse macrophages and human neutrophils). We used this system to measure the complex elastic modulus over bead displacement amplitudes ranging from 5 to 500 nm and twisting frequencies ranging from 10^{-2} to 10^{3} Hz.

The complex modulus did not change with displacement amplitude, implying linear mechanical behavior in this range. Elastic stresses dominated at frequencies below 300 Hz, increased only weakly with frequency, following a power law. Frictional stresses were also weakly dependent on frequency below 10 Hz, but approached a viscous limit at higher frequencies.

Surprisingly, data for all cell types, frequencies, and interventions studied could be scaled onto universal master curves. This scaling identified these cells as soft glassy materials existing close to a glass transition, with an effective noise temperature, x, of about 1.2. Trap models of glassy materials [6] use the effective noise temperature to express the level of mechanical agitation, or noise, in the matrix relative to the depth of the energy wells in which metastable elements are trapped.

These results stand in contrast to current concepts in cell rheology in that 1) relaxation processes exhibited no intrinsic time-scale, implying stress relaxation going as the power law t^{1-x} [7], and 2) frictional stresses did not correspond to a viscous process [8, 9].

These findings support the novel hypothesis that cytoskeletal proteins can regulate cell mechanical properties by modulating the effective noise temperature of the matrix and, thereby, the ability of cytoskeletal elements to hop out of energy wells. The practical implications are that the effective noise temperature is an easily quantified measure of the ability of the cytoskeleton to deform, flow, and reorganize.

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