Supplemental Material

Imaging viscoelastic properties of live cells by AFM: Power-law rheology on the nanoscale

F. M. Hecht, a† J. Rheinlaender, a† N. Schierbaum, a W. H. Goldmann, b B. Fabry, b and T. E. Schäffer* a

a Institute of Applied Physics, University of Tübingen, Auf der Morgenstelle 10, 72076 Tübingen, Germany.
b Department of Physics, University of Erlangen-Nuremberg, Henkestraße 91, 91052 Erlangen, Germany.
† Both authors contributed equally to this publication.
* E-mail: tilman.schaeffer@uni-tuebingen.de

Fig. S1  Estimation of the viscous drag force acting on the cantilever, generated by the cantilever’s motion through the surrounding liquid, for the data shown in Figure 1. The tip velocity \(v_{tip}(t)\) was calculated as the time derivative of the tip position, \(z(t) - d(t)\). The viscous drag force \(F_{VD}\) was estimated from the tip velocity using \(F_{VD} = \mu v_{tip}\), where \(\mu\) is the viscous drag coefficient of the cantilever. For the cantilevers used here, the drag coefficient was determined as \(\mu = 6.2 \text{ pN (\mu m/s)}^{-1}\) in a separate measurement (data not shown). We found that for the conditions used here, the influence of the tip-sample distance on the drag coefficient was negligible.

Fig. S2  Correlation of modulus scaling parameter \(E_0\) and power-law exponent \(\beta\) vs sample slope and height for the cell shown in Figure 2. (a) Image of the sample slope, \(((dz/dx)^2 + (dz/dy)^2)^{1/2}\). (b) \(E_0\) and (c) \(\beta\) as a function of sample slope. Neither the modulus scaling parameter \(E_0\) nor the power-law exponent \(\beta\) show a significant correlation with sample slope. (d) \(E_0\) and (e) \(\beta\) as a function of sample height. \(E_0\) and \(\beta\) show a visible correlation only for heights smaller than about 500 nm (red line).
Fig. S3 Maps of the apparent Young’s modulus $E$ of (a) the polyacrylamide (PAA) gel from Figure 2 and (b) the MEF vin-/- cell from Figure 3, obtained when applying a purely elastic contact model to the approach part of the force-distance curves. The Young’s moduli are slightly larger than the respective modulus scaling parameters (Figure 2 and Figure 3, respectively).

Fig. S4 Force clamp force mapping (FCFM) on the same polyacrylamide (PAA) gel as in Figure 2, but recorded with a DNP type cantilever. (a) Map and histogram of the modulus scaling parameter $E_0$. (b) Map and histogram of the power-law exponent $\beta$. Pixel resolution is $20 \times 20$ pixels. The mean values ($E_0 = 6.4$ kPa and $\beta = 0.092$) are in well agreement with the values obtained with the MLCT type cantilever from Figure 2 ($E_0 = 5.3$ kPa and $\beta = 0.091$), demonstrating the reliability of the FCFM method. The small difference in $E_0$ could be explained by the inaccuracy in the determination of the cantilevers’ spring constants (typically 10 – 20%).
Fig. S5  Power-law parameters $E_0$ and $\beta$ for different experimental parameters. (a) Map of contact height $z_c$ of a MEF WT cell. (b) Modulus scaling parameter $E_0$ and (c) power-law exponent $\beta$ for different experimental parameters $F_{\text{Clamp}}$, $\Delta t_{\text{Clamp}}$, and $v_{\text{Appr}}$ recorded within a small region on the cell (5 $\mu$m $\times$ 5 $\mu$m, 10 $\times$ 10 pixels, marked by the box in panel a). Median ± standard deviation is shown. Neither the mean values nor the standard deviations depend considerably on the different experimental parameters.

References