Supplementary Material (ESI) for Soft Matter

Supporting information

Elasticity Mapping of Apical Cell Membranes

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Theoretical considerations. Bending of a thin plate with a point load force produces the following linear relationship between force *F*(*h*) and indentation depth *h* (Figure 1s):

$$F(h) = \frac{4\pi E t^3}{3(1-\nu^2)R_{pore}^2} h \tag{1s}$$

E denotes the elastic modulus (Young's modulus), ν the Poisson ratio (ν = 0.33), R_{pore} the pore radius, and *t* the thickness of the bilayer. If bending dominates the elastic response of a cell membrane a linear regression at low load is justified and as a consequence k_{app} is given by:

$$k_{\text{app}} = \frac{4\pi E t^3}{3(1-\nu^2)R_{pore}^2} \, .$$

However, stretching is a major contribution to the elastic response at larger indentation forces described by the nonlinear membrane theory (Figure 1s):

$$F = \frac{9\pi E t}{16 R_{tip}^2 \left(R_{pore} / R_{tip} \right)^{\frac{9}{4}}} h^3 \, . \tag{2s}$$

R_{tip} is the tip radius. The linear combination of equations (1s) and (2s) provides a means to fit the data in order to obtain values for *E* and *t* (Figure 1s/2s):

$$F(h) = \frac{4\pi E t^3}{3(1-\nu^2)R_{pore}^2} h + \frac{9\pi E t}{16 R_{tip}^2 \left(R_{pore} / R_{tip} \right)^{\frac{9}{4}}} h^3 \, . \tag{3s}$$

The simulation clearly shows that up to an indentation depth of 50-100 nm the assumption of plate bending leading to linear force indentation curve is justified.

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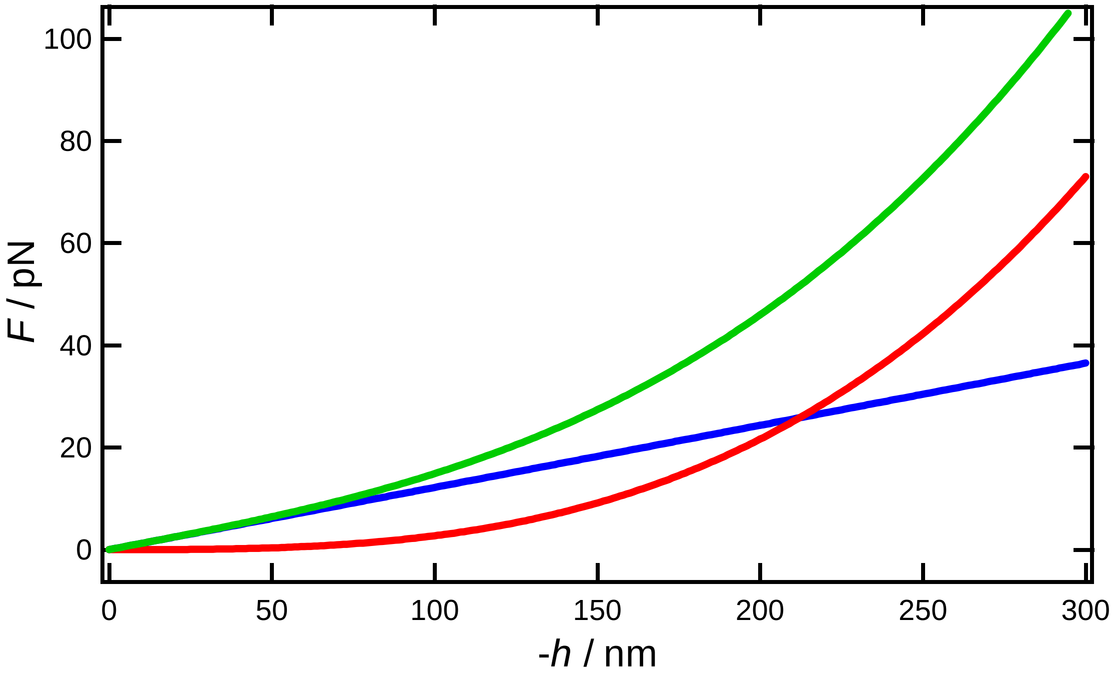

Figure 1s. Computed force indentation curves corresponding to equations (1s-3s). The green curve (equation 3s) is a linear combination of pure bending dominated indentation represented by the linear plate theory (equation 1s) and nonlinear membrane theory assuming that stretching occurs at higher load (equation (2s)). Parameters: R_{pore} = 600 nm, R_{tip} = 20 nm, E = 15.2 kPa, $\kappa = 7\times10^{-19}$ J, t = 85 nm.

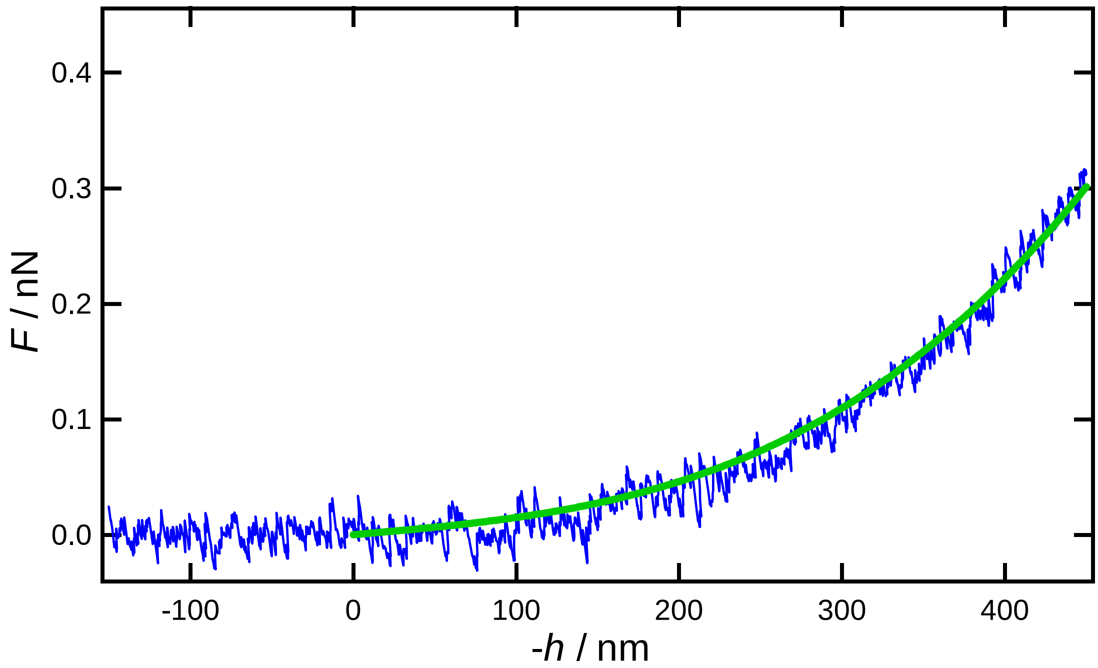

Figure 2s. Fit of the parameters of equation (3s) to an experimentally obtained force indentation curve taken on a pore covering apical cell-membrane. Parameters: R_{pore} = 600 nm, R_{tip} = 20 nm, E = 15.2 kPa, $\kappa = 7\times10^{-19}$ J, t = 85 nm.

Interpretation of the hysteresis between indentaion and relaxation. A three-body viscoelastic model with a time constant of η/k = 0.04 s is used to qualitatively understand the observed indentation and relaxation behavior of pore spanning cellular membranes. A linear spring illustrating bending of the bilayer is connected in series to a nonlinear spring representing the stretching of the bilayer and a Kelvin-Voigt model consisting of a parallel combination of a dashpot (η) and a spring (k) leading to the following force indentation $F^{\mathrm{ind}}(h)$ or force relaxation $F^{\mathrm{relax}}(h)$ relations:

$$F^{ind}(h) = \frac{4\pi E t^3}{3(1-\nu^2)R_{pore}^2} h + E R_{pore} \frac{\pi}{3} t \left(\frac{h}{R_{pore}} \right)^3 + F_{KV}^{ind}(h)$$

$$F^{relax}(h) = \frac{4\pi E t^3}{3(1-\nu^2)R_{pore}^2} h + E R_{pore} \frac{\pi}{3} t \left(\frac{h}{R_{pore}} \right)^3 + F_{KV}^{relax}(h)$$

with

$F_{KV}^{ind}(h)$ and $F_{KV}^{relax}(h)$ from solution of the Kelvin-Voigt model ($F(t) = kh + \eta \, {}^{dh}\!/_{dt}$)

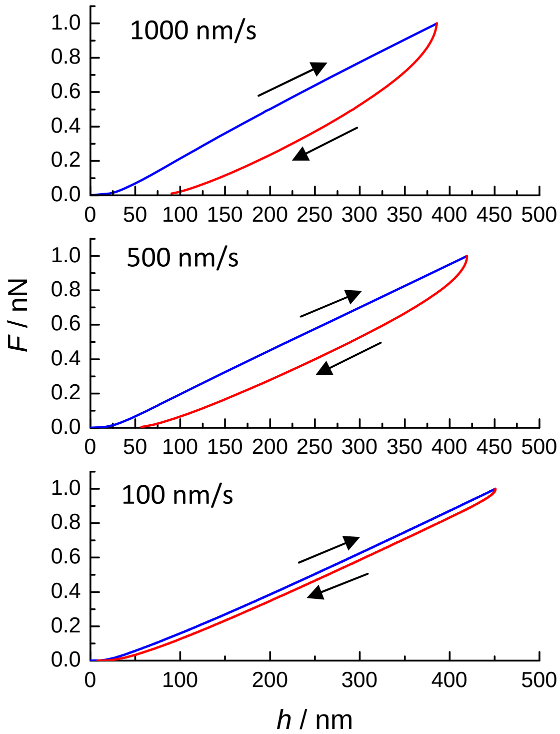

Figure 3s. Calculated indentation and relaxation curves of a nonlinear Kelvin-Voigt Model as a function of indentation velocity. Due to the small time constant (0.04 s) the hysteresis increases with increasing velocity as observed on the pore-spanning cell membrane.