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Deformation of Biconcave Red Blood Cell in the Dual-Beam Optical Tweezers



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Content

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Manipulating the human red blood cell (RBC) with optical tweezers

RBC (erythrocyte) → Transportability → Deformability → Mechanical force of cell

Optical traps → Mechanical force of cell

Red blood cells in the spleen

Scanning electron microphotograph of normal murine red blood cell passing from a splenic cord (below) through the sinusoidal barrier and into the splenic sinusoid (above). Note the deformation necessary to squeeze through the slit in the sinusoidal wall and how a surface area depleted spherocyte would be incapable of transversing the barrier. *Courtesy of Mohandas Narla, ScD.*

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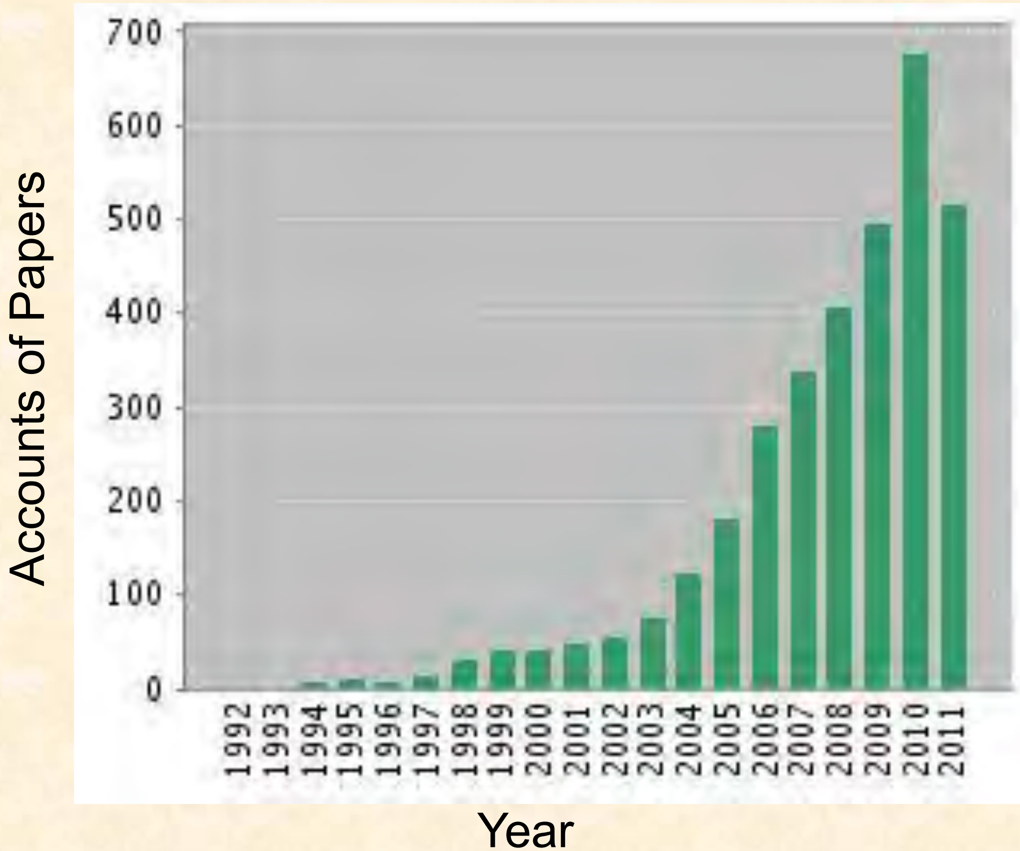
Cited papers about manipulating the RBC with optical tweezers



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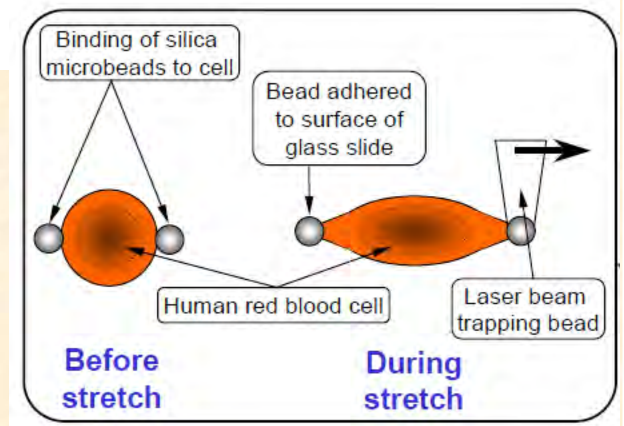
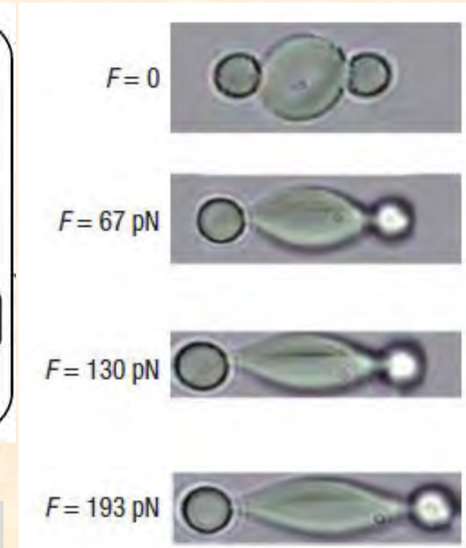
Manipulating RBC with optical tweezers

Beads contact

Without beads contact

*





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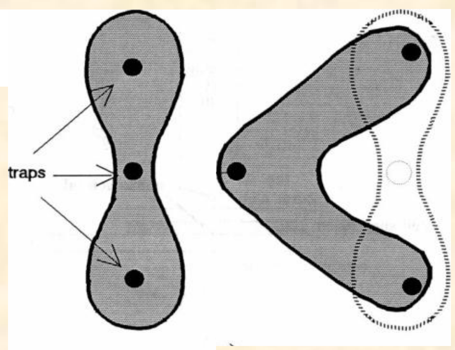

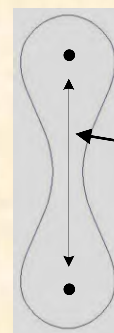

Dual- beam

‡

* : M. Dao et al, J. Mech. Phys. Solids 51(11-12), 2259–2280 (2003);

†: P. J. H. Bronkhorst et al, Biophys. J. 69 (5), 1666–1673 (1995);

‡: G. Liao et al, opt. expr. 16 (3), 1996-2004 (2008)

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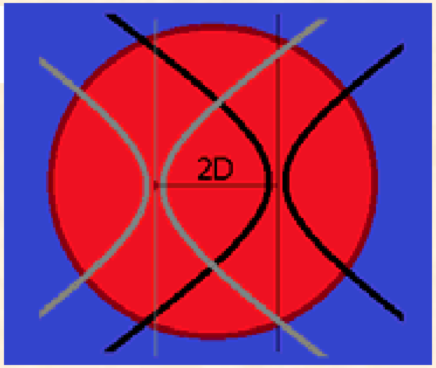
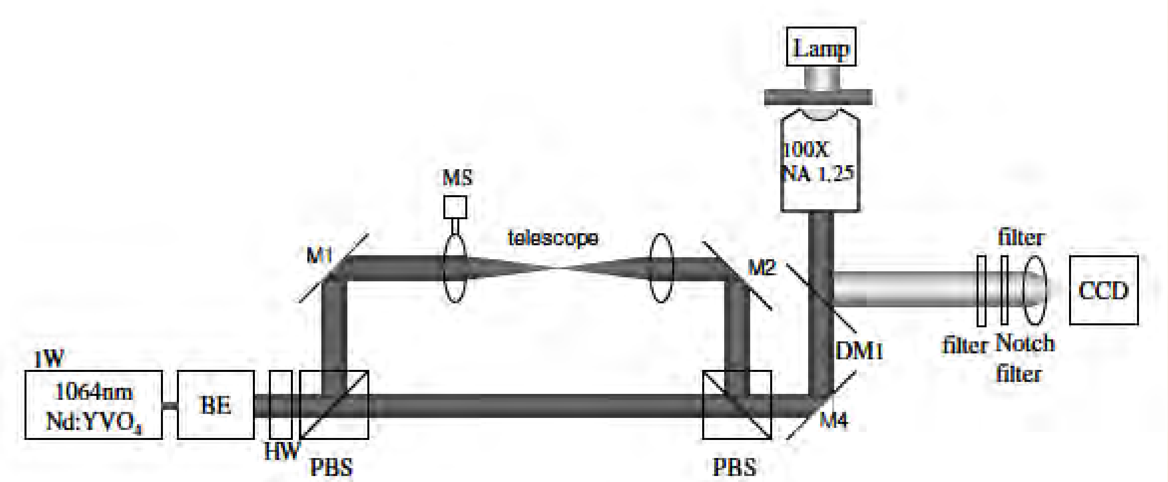
Dual-beam optical tweezers

‡





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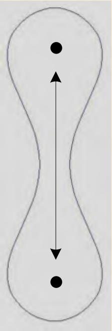

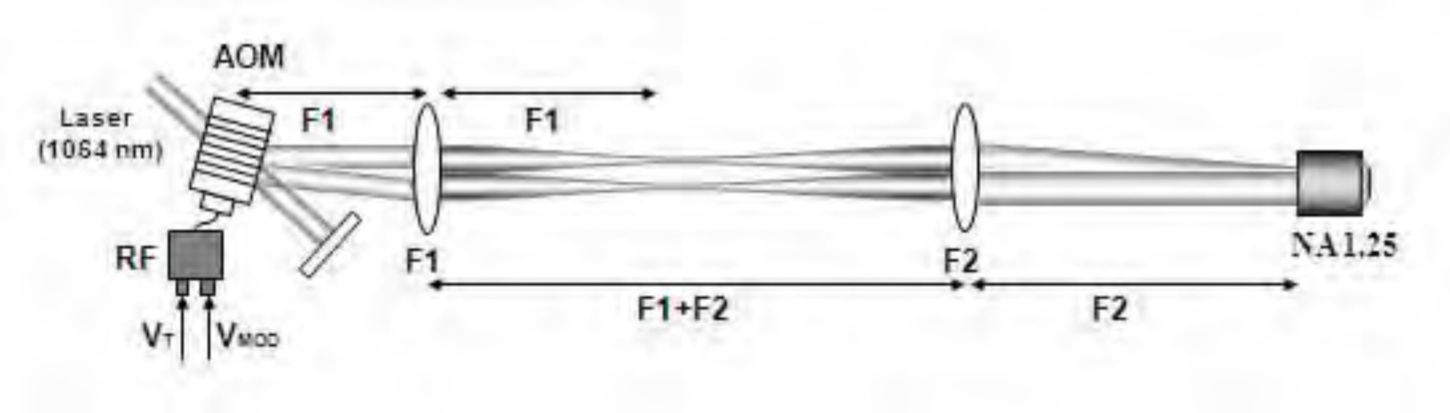

Jumping beam

†: G. B. Liao et al, Opt. Express 16(3), 1996–2004 (2008);
‡: Y. Sheng at el, COMSOL Conference Boston (2010).

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Advantages of the dual-beam optical tweezers

- Probing the characteristics of the cellular membrane and cytoskeleton by Manipulating living biological cells
- No physical contact to the specimen
- Photonics' shear force is in the same order of magnitude (pN) as the mechanical force for deforming the cell

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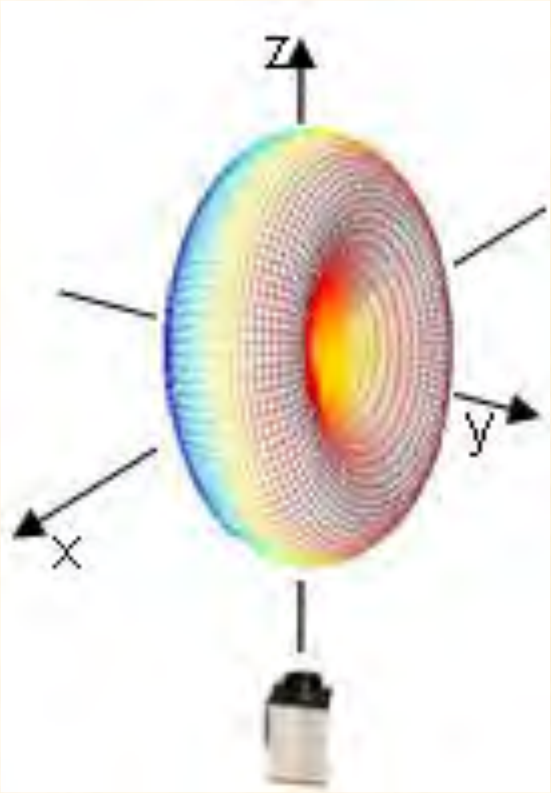
Steps of Simulation

1. Geometric construction of the biconcave human RBC
2. The background electromagnetic fields of dual-beam optical tweezers;
3. Compute stress distribution with Maxwell Stress tensor in RF Module^{TM}
4. Compute Deformation of RBC with solid mechanics^{TM} module

Geometry of a biconcave RBC



$$y = \pm D_0 \sqrt{1 - \frac{4\left(x^2 + z^2\right)}{D_0}} \left[c_0 + c_1 \frac{x^2 + z^2}{D_0^2} + c_2 \frac{\left(x^2 + z^2\right)^2}{D_0^4} \right]^*$$

D_0= 7.8 µm,

c_0= 0.207161,

c_1= 2.002558,

c_2= -1.122762.

* : E. Evans, and Y. Fung, Microvascular research, 4 (1972) 335-347

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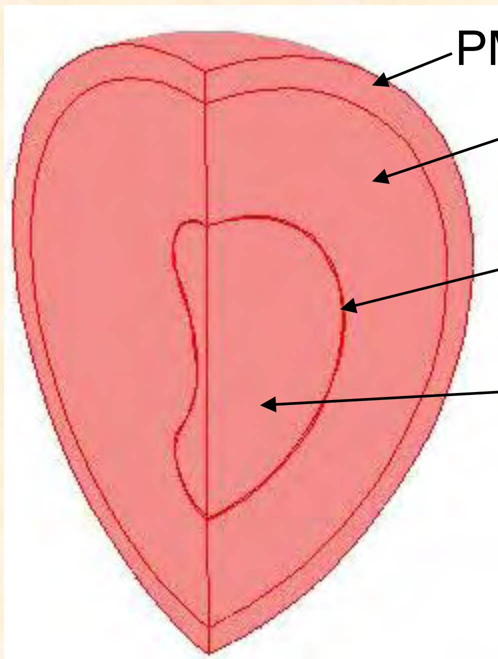
RBC model



PML

Buffer

RBC membrane

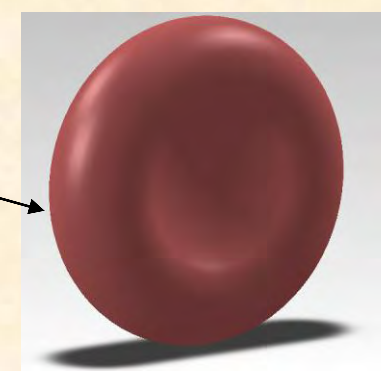
cytosol

$n_1=1.335$

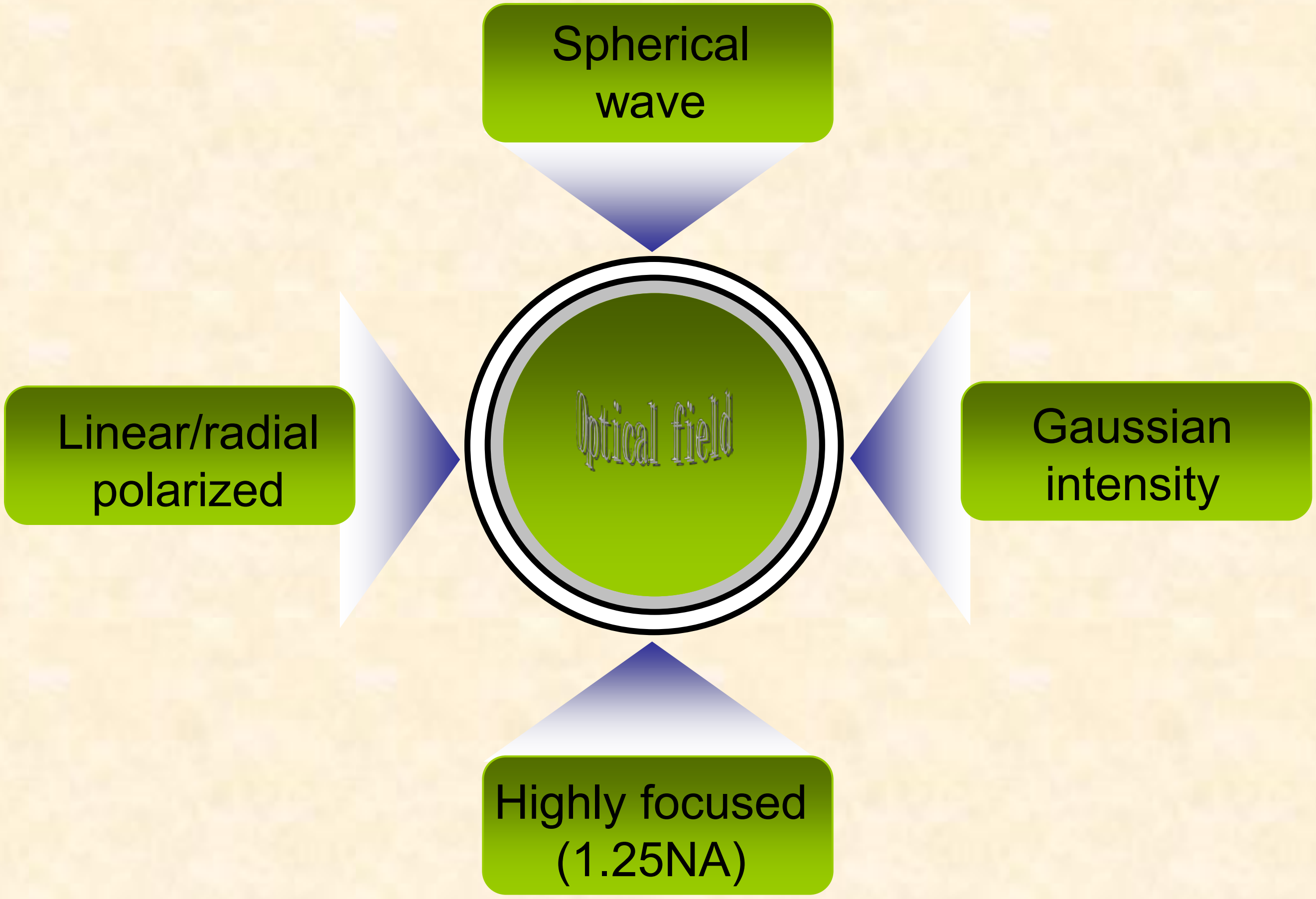
$d=1.5\%D_0$

$n_2=1.378$

RBC solid geometry



Introduction of background field



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Introduction of background field

$$E_{b1} = A_1 \frac{W_0}{W(z)} \exp\left(-\frac{(x - S/2)^2 + y^2}{W(z)^2} \right) \exp\left[j\frac{2\pi}{\lambda} \left[(x - S/2)^2 + y^2 + z^2 \right]^{1/2} \right]$$

$$E_{b2} = A_2 \frac{W_0}{W(z)} \exp\left(-\frac{(x + S/2)^2 + y^2}{W(z)^2} \right) \exp\left[j\frac{2\pi}{\lambda} \left[(x + S/2)^2 + y^2 + z^2 \right]^{1/2} \right]$$

Relative to beam power

Gaussian intensity

Spherical wave

$$W(z) = W_0 \left[1 + \left(\frac{z}{z_0} \right)^2 \right]^{1/2}$$

$$W_0 = \frac{\lambda}{\pi \tan\left(\sin^{-1}\left(\frac{NA}{n} \right) \right)}$$

$$z_0 = \frac{\pi W_0^2}{\lambda}$$

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Maxwell stress tensor

$$\overleftrightarrow{T} = \varepsilon\left[\vec{E}\vec{E} + \frac{1}{\varepsilon\mu_0}\vec{B}\vec{B} - \frac{1}{2}\left(E^2 + \frac{1}{\varepsilon\mu_0}B^2\right)\overleftrightarrow{I}\right]$$

$$\vec{\sigma} = \frac{\varepsilon_0}{2}\left(n_1^2 - n_2^2\right)\left(\left(\frac{n_1^2}{n_2^2}\right)E_n^2 + E_t^2\right)\vec{n}$$

tangent $\vec{E}_t = \vec{E}\times\vec{n} = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ E_x & E_y & E_z \\ n_x & n_y & n_z \end{vmatrix}$

normal $E_n = \vec{E}\cdot\vec{n} = E_x n_x + E_y n_y + E_z n_z$

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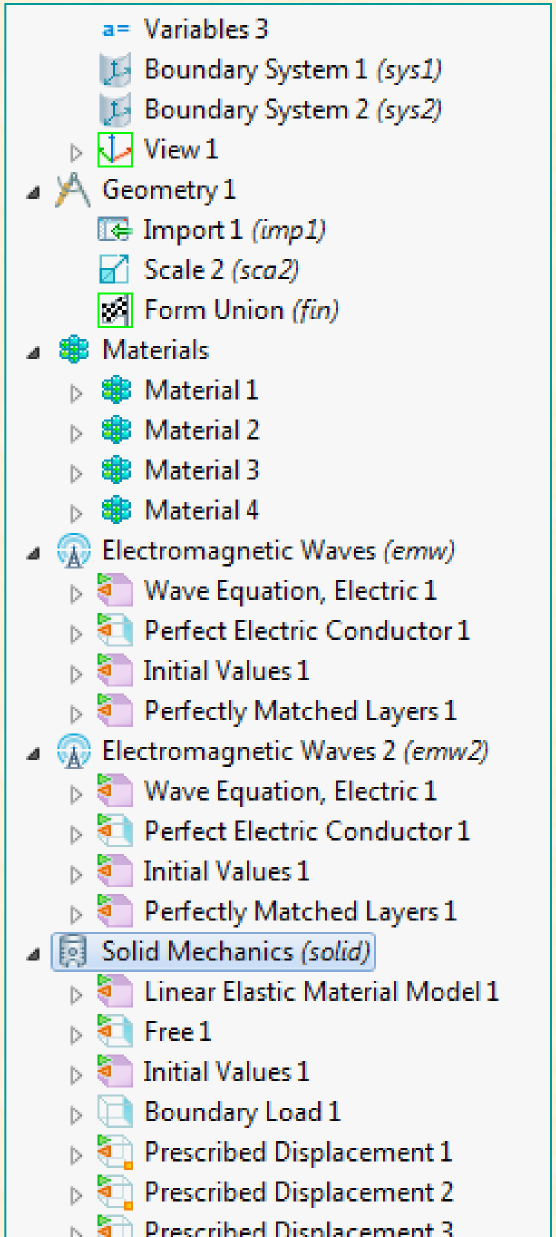
Interface of our model

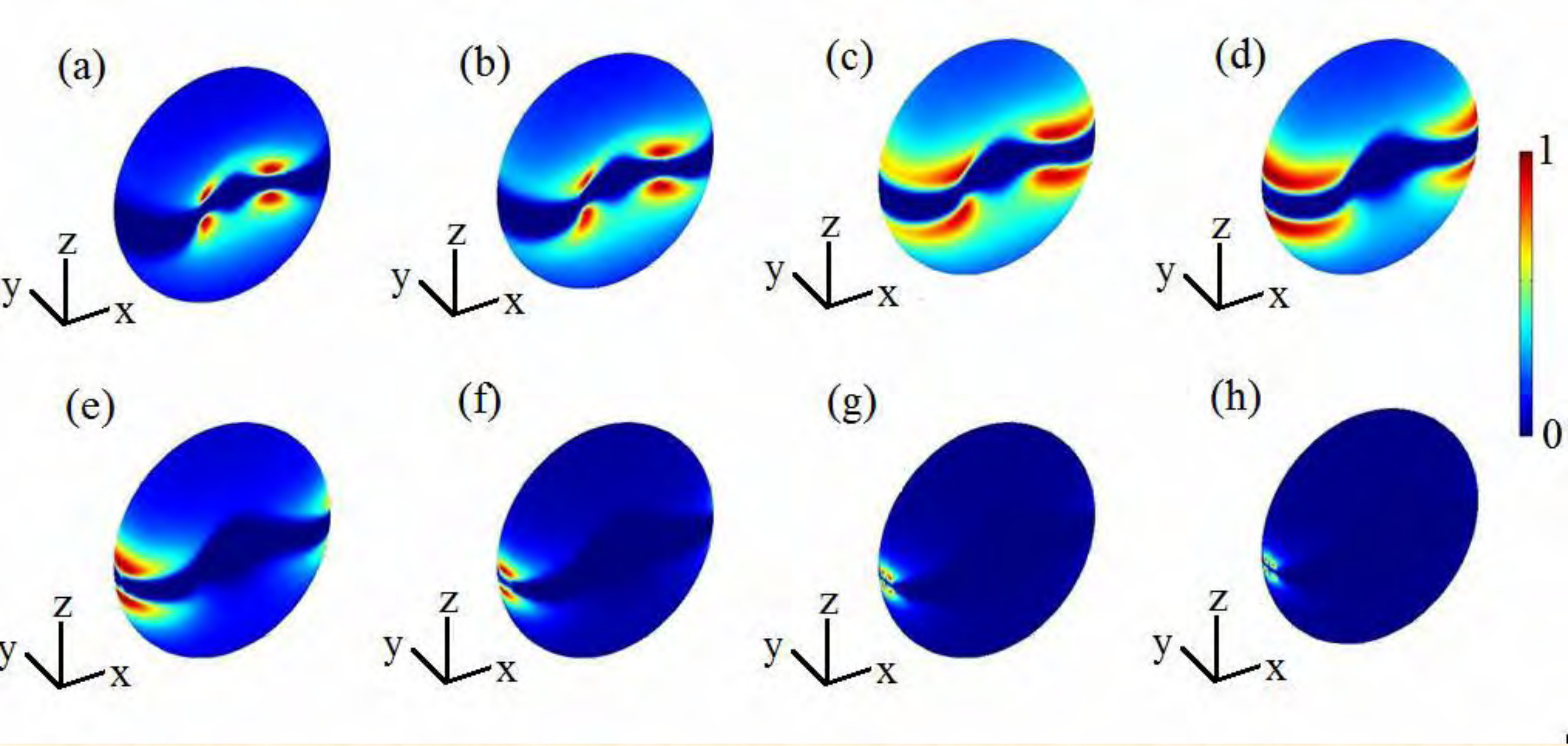


Two electromagnetic waves modules as dual-beam optical tweezers, respectively

Stress calculated from the RF modules will be loaded in Solid mechanics module

Constraints of prescribed displacement have also been set

Initial Stress on cell surface



The normalized stress distribution in different beam separations S=3.1 (a), 3.8 (b), 4.5 (c), 5.2 (d), 5.9 (e), 6.6 (f), 7.0 (g), and 7.3 (h) μm with COMSOL multiphysics.

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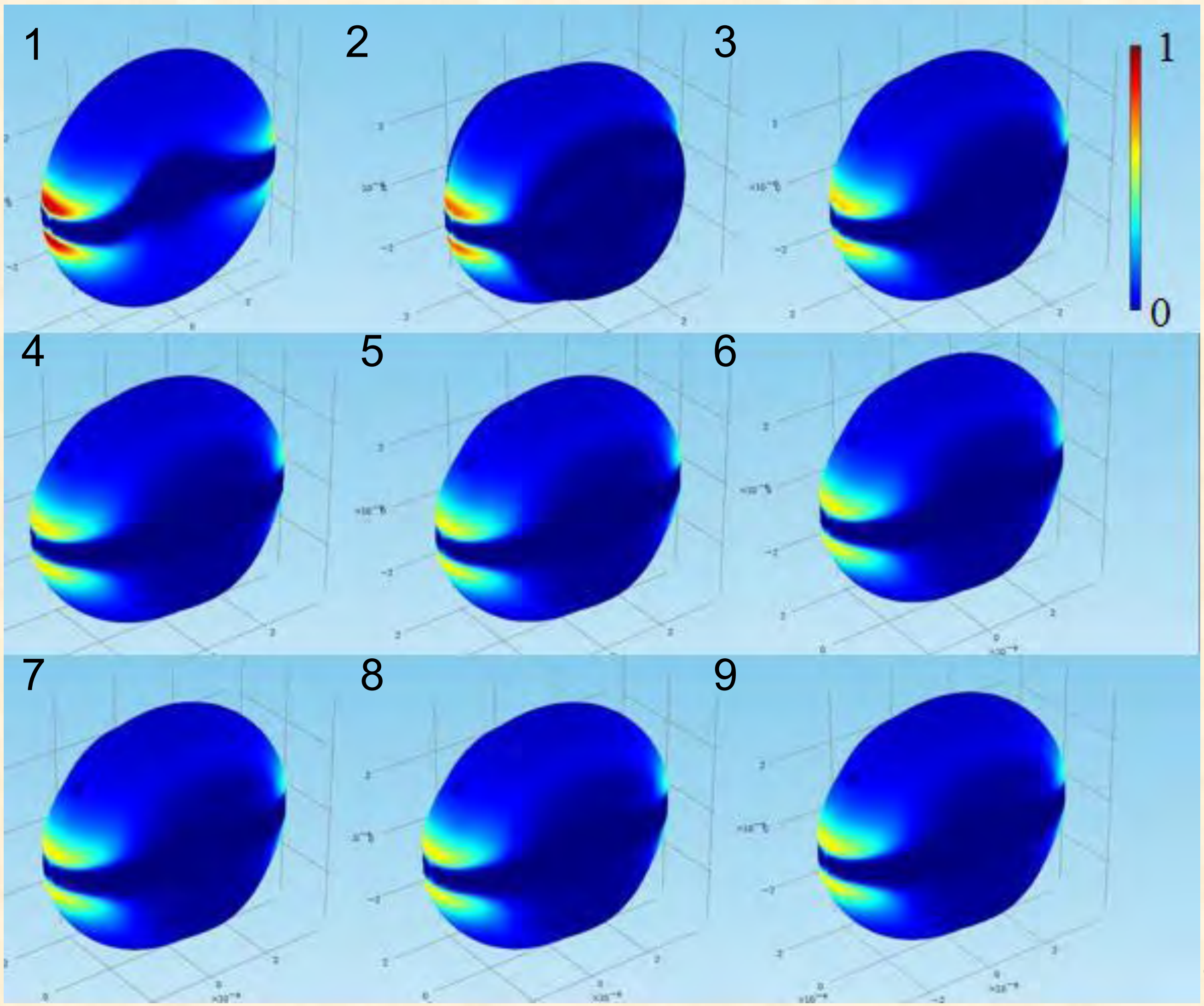
Redistribution of stress on the deformed cells



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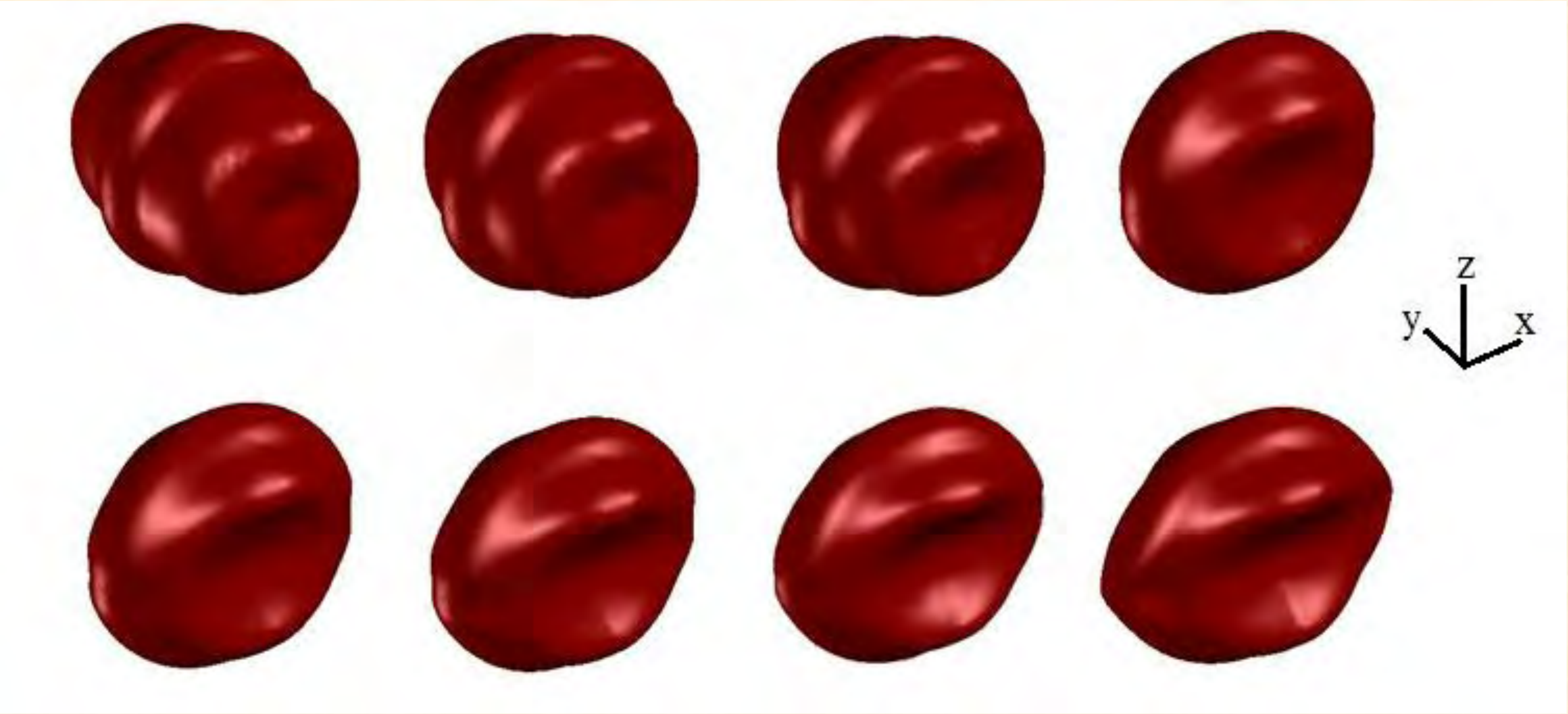
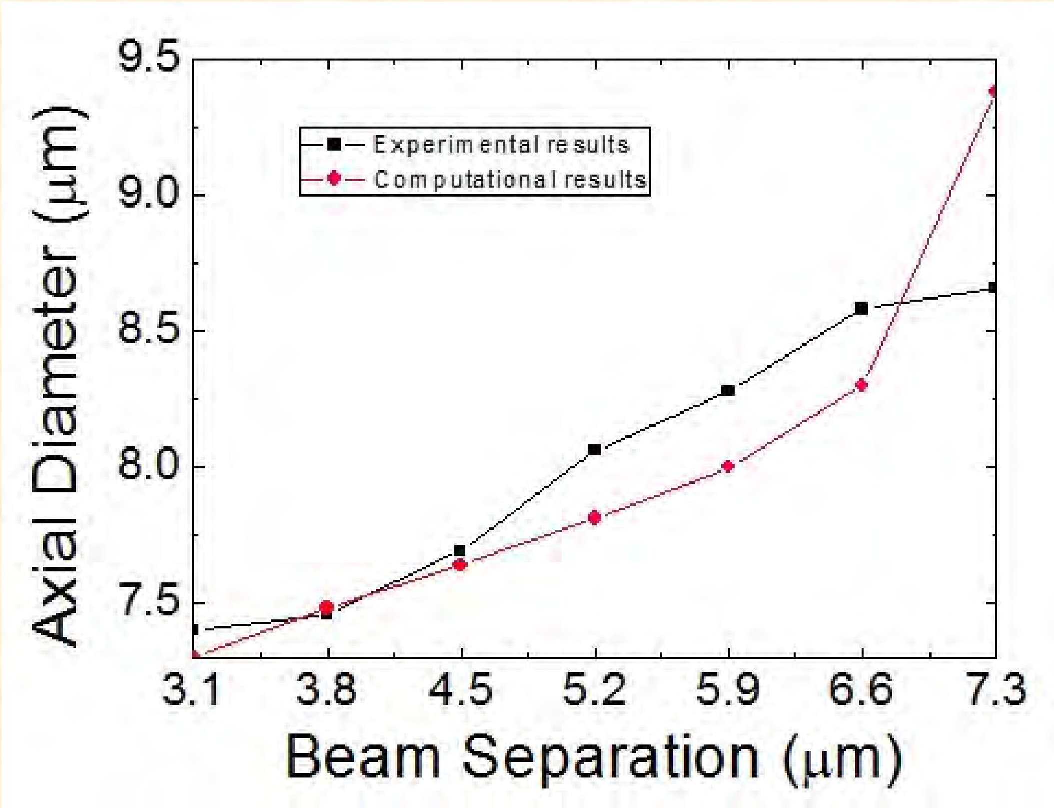
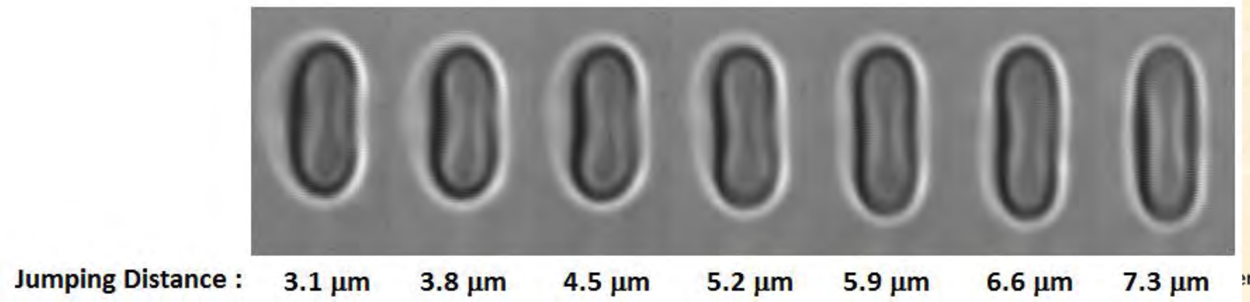
Final deformations



Fitting to Experimental Results



E= 650 Pa;
Eh=24μN/m;
Gh=17μN/m



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Conclusion

- RF module is used to compute the scattered EM field instead of geometrical optics;
- RF module and Structural mechanics module are combined with Comsol™ strongly coupled solver;
- Natural biconcave shape of RBC is calculated instead of the swollen spherical RBC;
- Computed deformations are fit to experimental data to determine the elasticity of the RBC .

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Prospects

- The deformation of the arbitrary shape of the cell can be simulated with the same method as well as the organelle and biomolecules (like the cell membranes, proteins, and DNAs).
- A variety of mechanical characteristics of human cells can be explored

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Thank you!