Optical Tweezers in Biophysical Context

Abstract: Optical tweezers can be used to move or fix small objects in a wide size range from single atoms to eukaryotic cells by the help of lasers. Due to radiation pressure acting in all different optical regimes a trapping force is generated. This principle can be used in various (biological) applications.

Laser exerts radiation pressure

The development of optical tweezers began with the work of Arthur Ashkin, who was therefore awarded the Nobel Prize in 2018. A laser can be considered as a point shaped light source which emits monochromatic and spatially coherent light into a distinct direction through stimulated emission. Lasers are able to exert force on particles due to the force on matter provoked from an electromagnetic field. The radiation pressure is found to be proportional to the intensity of the laser and the reflection coefficient. If the reflection coefficient is zero, the body is perfectly absorbing, if the coefficient is one, all momentum are doubled as the body is perfectly reflecting.

Trapping in optical regimes

A lens before the particle produces a focused Gaussian beam in all three dimensions which allows to trap cells in its center as shown in Figure 1. To describe the arising forces, three optical regimes play a role. If the diameter of a particle is much bigger than the wavelength of the laser, the regime is called Ray regime. The Rayleigh regime covers the case when the diameter is much smaller than the wavelength of the laser. The intermediate regime is the Mie-Lorentz regime, solutions in this regime are only possible with numerical approaches.

Rayleigh regime D << λ

In the Rayleigh regime, the objects can be described as a collection of dipoles. The forces which lead to the trapping are a gradient force and a scattering force which are both shown in Figure 1a. The latter is proportional to the photon flux and points towards the direction of the laser beam. The gradient force arises from the electrostatic potential and is pointing towards the highest intensity of the beam inducing trapping at this point.

Ray regime D >> λ

In the Ray regime, refraction and reflection play an important role inducing momentum change. In Figure 1b, the two rays are representative for the focused Gaussian beam. Therefore, the particle can be trapped by the refraction and reflection forces as their sum, considering all rays, always points towards the highest intensity of the beam.

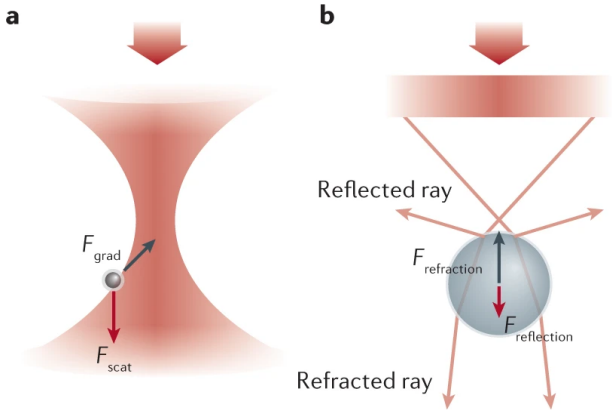

Fig. 1: Spherical objects in an optical trap [4]
a) Rayleigh regime b) Ray regime

Biological application

When using optical tweezers in biological application, the trapping force is approximated by a spring constant which is proportional to the displacement. The most common method is to use a quadrant photo diode to determine the latter. The following two examples show that optical tweezers are useful to measure dynamic processes, weak forces in experiments which are close to physiological conditions.

Motor protein kinesin

It is possible to trap a microsphere by optical tweezers which is transported by a kinesin motor protein. In 1990, Arthur Ashkin estimated the force of a kinesin motor protein to be 2.6pN [2] whereas in 1994 with a different measurement of the microsphere' displacement it was described to be $4-5$pN by [9]. The length of the kinesin step size was estimated to be 8µm in 1997 [7] whereas in 2021, 4µm substeps were hypothesized [8].

Optical stretcher

In this application, two identical, non-focused laser beams opposed to each other are used to stretch whole cells. The stretching forces arise from a momentum transfer of laser light to the surface. Other forces cancel out since the setup is symmetric. The optical deformability can be extracted and used to distinguish normal, cancerous and metastatic cells. As a result, an optical stretcher is able to determine the percentage of malign cells. Possibly, this method will be used for cancer diagnosis in the future.

References

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