Mapping of Three-Dimension Optical Force Field on Micro-particle in Optical Tweezers

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Abstract
We use a pair of orthogonal tracking beams to track and analyze the Brownian motion of a micro-particle or a living cell trapped in optical tweezers to map the three-dimensional optical force field on these samples. For optical trapping with $\lambda = 532\text{nm}$, $\text{NA} = 0.85$, and total power = 100mW, the axial and the transverse spring constants are around $1\times10^{-8}\text{ N/m}$ and $2\times10^{-8}\text{ N/m}$, respectively for a silica particle (diameter = $2.58\mu\text{m}$), and $3\times10^{-8}\text{ N/m}$ and $2\times10^{-7}\text{ N/m}$, respectively for a Chinese hamster ovary cell (diameter $\sim 15\mu\text{m}$).

Keywords: Optical tweezers, Orthogonal tracking, three-dimension optical force field, Chinese hamster ovary (CHO) cell

In 1986, Ashkin et al. demonstrated a single-beam gradient force optical trap (also known as optical tweezers) for the trapping of a micro-particle in a strongly focused (NA>0.6) Gaussian beam [1]. It was later demonstrated that optical tweezers can be used not only for non-invasive trapping of biological samples including living cells but also for the measurement of forces (on the order of pico-Newton) between biology samples [2, 3].

Optical forces on a micro-particle in optical tweezers are often calibrated by either dragging the trapped particle against a known viscous force [2, 3] or by tracking the Brownian motion of a trapped particle and analyzing its position distribution [4, 5]. In this paper, we report the first experimental demonstration of the tracking with a pair of orthogonal tracking beams of the motion of a particle or a living cell in optical tweezers and the analysis of its position distribution to map the three-dimensional optical force field on these samples.

The key components of our experimental setup are illustrated schematically in Fig. 1. A collimated laser beam ($\lambda=532\text{nm}$) focused by a microscope objective lens OB I (60X, NA=0.85) is used for trapping the sample and its forward scattering component collected by a second objective lens OB II (20X, NA=0.4) and projected onto a quadrant photodiode (QPD I) is used to track the motion of the trapped particle in the transverse (xy) plane. A second laser beam (from a He-Ne laser, $\lambda=632.8\text{nm}$) orthogonal to the trapping beam is focused on the trapped particle by a long working distance objective lens LOB I (100X, NA=0.55), and its forward scattering component collected by another long working distance objective lens LOB II (80X, NA=0.5) onto the second quadrant photodiode (QPD II) to track the motion of the trapped particle in the xz plane. The optical power of the tracking He-Ne laser beam is kept as low as possible ($\sim 1\text{mW}$ or less) so that its effect on the trapped particle is minimized.

The QPD output voltage was converted into particle displacement from its Lorentzian power spectrum $S_c(f) = k_b T / \beta^2 6 \pi \eta r (f_r^2 + f^2)$ [4] as is illustrated in Fig. 2(a).

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The main advantages of using a pair of orthogonal tracking beams (with two QPDs oriented perpendicular to each other) include 1. Each QPD is responsible for tracking the particle motion only in the transverse plane (in contrast to the single-beam tracking reported earlier [5]); 2. The intrinsic redundancy of experimental data in the common axis of the two QPDs (x-axis in the case of Fig. 1) can be used as an indicator for possible experimental errors (or noise). An illustrative example is given in Fig. 2 (b) where the Brownian motion of a trapped particle along the x-axis deduced from one QPD is plotted against those deduced from the orthogonal QPD.
Ideally, the result should be a straight line through the origin. Deviation of the experimental data from the straight line is an indication of the experimental errors (or noise) involved in the system. Such a calibration curve can be used as a vehicle to fine-tune the optical alignment to minimize the noise and the error. The projections of the 3-dimensional Brownian motion of a trapped silica particle on the xy plane (tracked by QPD I) and on the xz plane (tracked by QPD II) are depicted in Fig. 2 (c) and (d), respectively.

Fig. 2. a) QPD output voltage power spectrum. b) The Brownian motion of a trapped silica particle (diameter = 2.58 µm) along the x-axis deduced from QPD I against that deduced from QPD II. c) The Brownian motion of a trapped particle in the xy-plane tracked by QPD I. d) The Brownian motion of a trapped particle in the xz-plane tracked by QPD II.

We assume that the optical force field can be represented by a three-dimensional harmonic potential well, and use Boltzmann statistics to calculate the spring constant of optical force field along each axis via the following two equations

$$\rho(x) = C \exp\left[-E(x)/k_B T\right]$$

$$E(x) = -k_B T \ln \rho(x) + k_B T \ln C = k_x x^2 / 2$$

Where $\rho(x)$ is the probability function of the particle position along the x-axis, $C$ is the normalization constant, $E(x)$ is the potential energy function along the x-axis, $k_B$ is the Boltzmann constant, and $k_x$ is the spring constant along the x-axis.

Experimental data along with the corresponding theoretical fits are depicted in Fig. 3 for the case of a Chinese hamster ovary (CHO) cell which is chosen as a convenient cell model for the study of cellular interaction with surrounding bio-molecules. The dependence of optical force constants on optical power, on the size of the particle, and on different types of cell of interest will be presented.

Fig. 3. The three-dimension optical force field on a CHO Cell trapped in optical tweezers. "○": optical trapping potential energy along the x-axis with spring constant $K_x = 2.49 \times 10^{-7}$ N/m; "×": optical trapping potential energy along the y-axis with spring constant $K_y = 2.09 \times 10^{-7}$ N/m; "+": optical trapping potential energy along the z-axis with spring constant $K_z = 3.09 \times 10^{-8}$ N/m.

References