Helical Bacteria as Optically Driven Microrotors

H. Schmitzer*, J. Swearingen*, J. Robbins**, D. Engle*, W. Dultz***, D. Tierney*

Xavier University, Cincinnati, OH 45208

*** St. Mary's College of California, Moraga, CA 94575*

**** Goethe Universität, Frankfurt a. M., D 60054*

mailto:schmitzer@xavier.edu

The linear momentum transfer from photons to micrometer sized helical bacteria, which are held in optical tweezers, can make them rotate very quickly. This forced rotation can be compared to the screw like motion of free, living bacteria. We describe our experiments and investigate the driving force of the rotation.

1 Introduction

Recently, micromechanical elements which are rotated with light have been suggested as optically driven motor. An opto-mechanical rotation can be generated by spin angular momentum transfer to birefringent, micron-scale objects [1], by orbital angular momentum transfer from helically wound light beams [2] and by linear momentum transfer to asymmetrically shaped structures [3]. The production of such structures is, however, costly and difficult; instead, one could use various asymmetrically shaped bacteria or cells, since they can be easily grown and mass-produced. The helical bacterium *Rhodospirillum rubrum* can be simply and very quickly rotated by the linear momentum transfer from light when held in optical tweezers [4]. We investigate this driving mechanism and compare their forced rotational motion in optical tweezers with the rotational motion of the living, non-tweezed bacteria.

2 Experiment

Our optical tweezers consisted of a Helium-Neon-Laser which was focused through a 63x microscope objective. The focus had a diameter of approximately $0.9\ \mu m$ and $25\ mW$ power. This microscope lens was also used to observe and film the bacteria. The intense laser beam holds the bacterium as with tweezers, but allows it to rotate freely around its own axis. *R. rubrum* ranges in length from about $2 - 5\ \mu m$ and its body is roughly 0.5 µm in diameter, with roughly one helical turn per cell and a left-handed helical pitch of approximately 2 µm. Its bipolar flagella can rotate in either direction to move it through surrounding fluid in a corkscrew-like fashion [5]. A droplet of a solution containing the bacteria was placed between a slide and cover glass sealed together to reduce bulk flow. This sample was then placed in the focus of the optical tweezers.

We observed a number of living *R. rubrum* cells and measured their rotational speed while moving and spinning forward freely and then trapped them in the focus, where they oriented vertically upon capture and started to spin. We also measured the rotational speed of this forced spinning motion and then compared it to the free rotational speed when the bacteria were alive (Abb.1). The living bacteria can of course vary their rotational and translational speed, but the graph still shows that the speed with which the bacteria rotate on their own is of the same order of magnitude as their speed in the optical tweezers. This is interesting, because it allows us to draw conclusions about the force exerted by the flagellar motor itself. In order to do so we calculate how much force of the 25 mW is actually used to rotate the bacteria in the focus at a speed similar to their own.

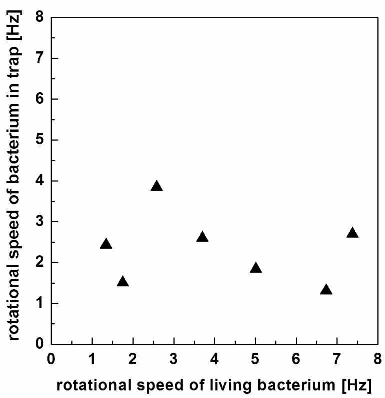

***Abb. 1** Comparison of the forced rotation in the optical trap versus the rotational speed of free bacteria. Each data point represents one bacterium.*

3 Theory

Linear momentum transfer from the incident laser light causes the helical bacterium in the optical trap to rotate. The photons which are reflected from the membrane transfer linear momentum to the inclined rod shaped body of the bacterium. In a first approximation we treat the helical bacterium like an inclined plane and neglect its circular cross section. In this case each reflected photon induces a force component perpendicular to the helix -and thus a torque- that is given by

$$F_{\perp} = 2\hbar k \cos\theta \cos\theta \qquad (1)$$

where $\theta \approx 40^\circ..60^\circ$ is the slope angle of our helical bacteria. Within this range the induced force component given by (1) does not vary much, but on the other hand the number of photons that are reflected increases considerably for steeper slopes according to Fresnel's laws. If we assume a flat bacterium of width D and helical radius R, then the total force driving the rotational motion is given by

$$\sum F_{\perp} = \frac{I}{c} 2\pi RD \cos\theta \ \sin\theta \ \left(r_s^2 + r_p^2\right) . \qquad (2)$$

I is the intensity incident on the surface $DL\cos\theta$, where the length L of the bacterium is replaced by $2\pi R/\cos\theta$ to give the effective cross section $2\pi RD$ of one pitch. And $r_s\left(n_i, n_t, \theta\right)$ and $r_p\left(n_i, n_t, \theta\right)$ are the reflection coefficients for light polarized perpendicular and parallel to the plane of incidence, respectively. Both depend on the refractive index of the solution $n_i \approx 1.3$ and the refractive index of the membrane $n_t \approx 1.45..1.6$. They also vary with the incident and slope angle θ.

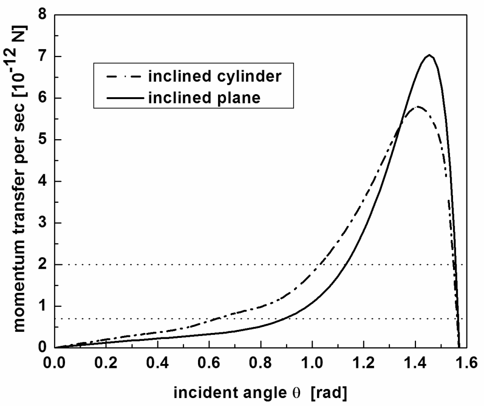

Abb. 2 *Dependence of the driving force on the slope angle of the helical structure. Solid line: force on a plane twisted as a helix. Dashed line: force on a cylinder twisted as a helix. The two curves differ roughly by a factor of 2 within the region* $\theta \approx (0.6...1.0)$ *rad of our bacteria.*

The solid line in Abb. 2 shows the angular dependence of the driving force according to this simple model. In a further step we took into account the cylindrical shape of the bacterium's body by integrating over curved surface elements. Equation (2) becomes then an integral which can be solved numerically. The dashed line in Abb. 2 represents this more elaborate model where the photon flux is reflected from a cylindrical surface. As the points of intersection with the dotted horizontal lines show, bacteria with a slope angle $\theta \approx 60^\circ$ are driven by a force that is three times as large as the force on bacteria with a slope angle $\theta \approx 40^\circ$. This may explain the variations in the terminal rotational speed of helical bacteria in the optical trap, which were reported earlier [4].

Measurements with a scale show that the cross section of a bacterium that is trapped and oriented in the focus has a diameter of about $1\ \mu m$. In addition, we do not see a hollow spot in the center of the helical bacterium when it is in the focus. Therefore the focus is smaller than the effective cross section and we assume that the bacterium is exposed to the full power in the focus. We can then estimate that our power of $25\ mW$ drives the rotation with a force between $(0.7...2.0)\ pN$.

4 Conclusion

We calculated the angular dependence of the driving force of the rotational motion of the bacterium *Rhodospirillum rubrum* in optical tweezers. As the name *rubrum* suggests, these bacteria scatter and reflect red light very well. Provided that the rotation is mainly driven by reflected photons, we estimated the magnitude of the driving force. Because the forced rotational speed is comparable to the free rotational speed of living bacteria, we may conclude that the force exerted by the flagella is of the same order of magnitude, namely $\leq 2.0\ pN$.

5 Support

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6 References

[1] M. E. J. Friese, T. A. Nieminen, R. N. Heckenberg, and H. Rubinsztein-Dunlop, Nature (London) **394,** 348 (1998).

[2] V. Garces-Chavez, D. McGloin, M. J. Padgett, W. Dultz, H. Schmitzer, and K. Dholakia, Physical Review Letters **91**, 093602 (2003).

[3] E. Higurashi, H. Ukita, H. Tanaka, and O. Ohguchi, Appl. Phys. Lett. **64**, 2209 (1994).

[4] J. R. Robbins, D. A. Tierney, and H. Schmitzer, Appl. Phys. Lett. **88**, 0239011 (2006).

[5] A. G. Lee, and J. T. Fitzsimons, J. Gen. Microbiology **93**, 346 (1976)