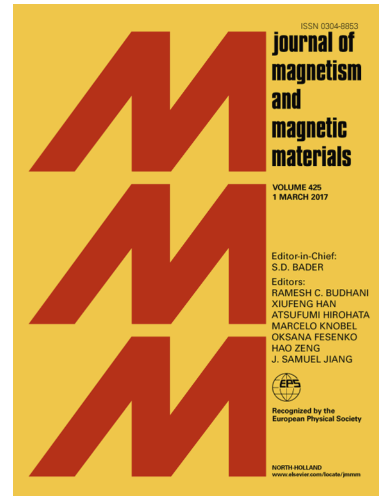

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Magnetic Response of *Magnetospirillum gryphiswaldense* observed inside a microfluidic channel

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Abstract

In this study we modelled and measured the U-turn trajectories of individual magnetotactic bacteria under the application of rotating magnetic fields, ranging in amplitude from 1 to 12 mT. The model is based on the balance between rotational drag and magnetic torque. For accurate verification of this model, bacteria were observed inside 5 µm tall microfluidic channels, so that they remained in focus during the entire trajectory. From the analysis of hundreds of trajectories and accurate measurements of bacteria and magnetosome chain dimensions, we confirmed that the model is correct within measurement error. The resulting average rate of rotation of *Magnetospirillum gryphiswaldense* is 0.74 ± 0.03 rad/mTs.

Keywords: Rotational magnetic torque, rotational drag torque, magnetotactic bacteria, microfluidic, control

1. Introduction

Magnetotactic bacteria [1] (MTB[1]) possess an internal chain of magnetosome vesicles [2] which biomineralise nanometer sized magnetic crystals (Fe_3O_4 or Fe_3S_4 [3, 4, 5]), encompassed by a membrane (magnetosome) [6]. This magnetosome chain (MC) acts much like a compass needle. The magnetic torque acting on the MC aligns the bacteria with the earth magnetic field [7]. This is a form of magnetoreception [8], working in conjunction with aero-taxis [9]. At high latitudes the earth's magnetic field is not only aligned North-South, but also substantially inclined with respect to the earth's surface [10]. The MTB are therefore aligned vertically, which converts a three-dimensional search for the optimal (oxygen) conditions into a more efficient one-dimensional search [11] (gravitational forces do not play a significant role at the scale of a bacterium). This gives MTB an evolutionary advantage over non-magnetic bacteria in environments with stationary chemical gradients more or less perpendicular to the water surface.

In this paper we address the question of how the MTB of type *Magnetosprilillum gryphiswaldense* (MSR-1) respond to varying magnitudes of the external field, in particular a field that is rotating. Even though the response of individual magneto-tactic bacteria to an external magnetic field has been modelled and observed [12, 13, 14, 7, 15], there has been no thorough observation of the dependence on the field strength. The existing models predict a linear relation between the angular velocity of the bacterium and the field strength, but this has not been confirmed experimentally. Nor has there been an analysis of the spread in response over the population of bacteria. The main reason for the absence of experimental data is that the depth of focus at the magnification required prohibits the observation of multiple bacteria in parallel. In this paper, we introduce microfluidic chips with a channel depth of only 5 µm, which ensures that all bacteria in the field of view remain in focus.

The second motivation for studying the response of MTB to external magnetic fields, is that they are an ideal model system for self propelled medical microrobotics [16, 17]. Medical microrobotics is a novel form of minimally invasive surgery (MIS), in which one tries to reduce the patient's surgical trauma while enabling clinicians to reach deep seated locations within the human body [18, 19, 20].

The current approach in medical microrobotics is to insert the miniaturized tools needed for a medical procedure into the patient through a small insertion or orifice. By reducing the size of these tools a larger range of natural pathways becomes available. Currently, these tools are mechanically connected to the outside world. If this connection can be removed, so that the tools become untethered, (autonomous) manoeuvring through the veins and arteries of the body becomes possible [21].

If the size and/or application of these untethered systems inside the human body prohibits the storage of energy for propulsion, the energy has to be harvested from the environment. One solution is the use of alternating magnetic fields [17]. This method is simple, but although impressive progress has been made, it is appallingly ineffi-

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[1] Throughout this paper we will use the acronym MTB to indicate the single bacterium as well as multiple bacteria